AN INVESTIGATION OF TURBULENCE STIMULATION AND EXPANSION SLOPES FOR A PLANING HULL SERIES

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****

BY

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LIST OF SYMBOLS

WL_c - After point of spray or waterplane intersection

WL_k - Intersection of water with keel

WL_s - Secondary chine, the point on the side where side wetting begins

WH_t - Wetted height of transom, measured in tenths of station spacing

L_m - The mean wetted length equals the average of length on the chine and length on keel.

λ - Linear ratio

R_t - Total resistance in pounds

Δ - Displacement in pounds

R_t/Δ - Specific resistance

ρ - Mass density, $\frac{\text{lb-sec}^2}{\text{ft}^4}$

ν - Kinematic viscosity, $\frac{\text{ft}^2}{\text{sec}}$

S_{tm} - Total wetted surface of model, ft^2

S_{ts} - Total wetted surface of ship, ft^2

C_t - Total resistance coefficient, $\dfrac{R_t}{\frac{\rho}{2} S V^2}$

Re - Reynolds No., $\dfrac{vL_m}{\nu}$

a/A - Blockage factor = $\dfrac{\text{area of largest section of model}}{\text{tank depth x tank width}} \quad \dfrac{ft^2}{ft^2}$

V/ L - Speed-length ratio, V is knots and L is the waterline length of the model at normal displacement in the still condition

r - Form factor based on Hughes friction formulation where

C_v, the viscous resistance = $\dfrac{.066}{(\log_{10}Re - 2.03)^2}$

τ - Change in trim, degrees

θ - Change in trim + shaft angle

LCG - Longitudinal center of gravity

EHP - Effective Horsepower

C O N T E N T S

INTRODUCTION

In the merchant ship field, it has been found that as a result of tests of small models and comparing their results with large models or full scale hull forms, a single line expansion based on the American Tank Towing Conference Line of 1947 (Schoenherr Line) or the International Towing Tank Conference Line of 1957 is unsatisfactory. A form factor determination such as proposed by Dr. G. Hughes is essential to obtain a correlation in test results.

If this condition is true for displacement hull forms, it should be true for planing models. This can only be investigated by means of testing and comparing results of geometrically similar models. A three dimensional analysis along with the turbulence stimulation problem are the reasons for this thesis.

The need for stimulation in the testing of planing hulls had not been thoroughly investigated at Webb Institute. All planing hull models tested during recent years had been stimulated by towing a .04 inch diameter strut 4 inches forward of the stem. This provided the simplest arrangement although the adequacy of stimulation was still questionable. A major portion of theses testing time was devoted to attempts to solve this most difficult problem.

It is the authors' hope that this thesis will point out the inadequacy of expansion to full scale by the 1947 American

Tank Towing Conference and the 1957 International Towing Tank Conference lines. It is further hoped that the tests of various stimulators and patterns will prove useful to future planing hull model constructors in the testing of their designs.

BACKGROUND

Testing of Series 56 models was completed several years ago at the David Taylor Model Basin. The purpose of this series was to test as wide a range of model sizes as possible for a planing hull. The lines of the PT 8 were chosen for this series. The choice was unfortunate from the standpoint of ease of model construction, checking, and testing. The mean shaft angle of the parent hull was 11.9° to the base line. The reason for the selection of the PT 8 as the parent hull was to allow a full scale trial check to be made on model predictions. The full scale data are in the process of analysis at DTMB.

A model of the PT 7 hull form was available at the DTMB and was modified to conform to the lines of PT 8. Four additional models were constructed and tested. The principal dimensions are given in Table I.

To further extend the range of higher linear ratios in this series, the authors constructed an additional model and tested it at Webb Institute of Naval Architecture. Dimensions of this model are also given in Table I.

Ta ble I

Model	Linear Ratio	DISPLACEMENT, LBS. Light	Normal	Heavy	Normal LWL Ft.	Heavy LWL Ft.	Max. Beam Ft.	Approx. Mean Beam Ft	Normal Draft Ft.	Heavy Draft Ft.
PT8	1	76,000	111,000	146,000	75	77.25	16,67	14.10	3.26	3.75
4023	4.5	811.2	1184.8	1558.4	16.67	17.17	3.70	3.10	.724	.834
4022	6.75	240.4	351.1	461.8	11.11	11.44	2.47	2.10	.483	.556
3592-1	9.0	101.4	148.1	194.8	8.33	8.58	1.85	1.60	.362	.417
4021	11.25	51.9	75.8	99.7	6.67	6.87	1.48	1.30	.290	.335
4020	13.5 0	30.1	43.9	57.7	5.55	5.72	1.24	1.10	.242	.278
Webb	27.0	--	5.49	7.21	2.775	2.86	.62	.55	.121	.139

Mean Buttock Angle 1.5°

LCG (Normal Condition) - 35.53 °/o from Station 10

LCG (Heavy Condition) - 40.80 °/o L from Station 10

CONSTRUCTION

The Lines Drawing included in the Appendix was prepared from the plans received from the David Taylor Model Basin. Waterlines for both normal and heavy displacement test conditions are indicated on this drawing.

The model was constructed from three lifts of clear sugar pine of approximately 1 3/4" thickness. The interior of two of the lifts was cut out before gluing. These cut out portions were mounted on a table and used to hold the model in alignment while under construction. The lifts were glued with Weldwood glue and placed in a gluing press.

Centerlines and stations were marked on the model and mounting table. Templates were made of Herlock cardboard for all stations as well as for the bow and stern. Special planes, gauges, files, chisels, and sandpaper were used in the construction. Because of the uniformity of the side taper, the sides were completed down to the chine line first and the bottom completed last. Battens were used to assist in fairing between stations.

Eight coats of clear spar varnish were used in finishing the model. After the first two coats were applied, sandpaper was used to remove most of the varnish. After subsequent coats, fine dry sandpaper was used. After each of the final two coats was applied, wet sandpaper was used to obtain a highly smooth surface. Three coats of varnish were applied to the interior

of the model as a seal against moisture.

Towing and accelerating strut brackets constructed of aluminum were installed on the model.

Station, half-station and heights on the transom were painted on the model to aid in reading chine points, and wetted heights of the transom during testing.

The small model constructed at Webb was checked on a leveling table at DTMB during the Winter Work Period. Actual measurements are compared with values computed from Buships drawing #374759 in Table II. The magnitude of the errors compared very favorably with tabulated errors on the DTMB models taken at the time of construction.

TABLE II

Comparison of Webb Model to Vaules Computed from BuShips Dwg 374759 All values in inches

Sta.	Comp. Keel to Chine	Meas. Keel to Chine Stbd	Meas. Keel to Chine Port	Comp. Half-Breadth	Meas. Stbd Half-Breadth	Meas. Port Half-Breadth
0	2.42	2.352	2.324	2.155	-	-
1	2.22	2.274	2.276	3.01	3.03	3.03
2	1.76	1.886	1.95	3.305	3.24	3.29
3	1.44	1.57	1.64	3.42	3.37	3.40
4	1.30	1.35	1.38	3.445	3.39	3.42
5	1.18	1.183	1.213	3.415	3.36	3.39
6	1.03	1.025	1.040	3.36	3.32	3.38
7	.855	.835	.841	3.275	3.24	3.31
8	.670	.646	.677	3.16	3.12	3.18
9	.485	.435	.474	3.015	3.00	3.13

Block Coefficient .47

TESTING PROCEDURE

This section will deal with procedures at the Webb Tank.

TANK The carriage at the Webb Tank is pulled by a string which is driven by a motor. The timed part of the run covers a distance of 35 feet. The water is heated to maintain a constant tank temperature of 80°F. Top speed is 15.5 fps. The planing model was not tested above 12.7 fps.

TEST CONDITIONS The Webb model was tested in two conditions of trim and displacement:

*NORMAL	HEAVY	LCG FWD. OF STA. 10
5.5 # No Trim	7.21 # .9° x Bow	35.53% - Normal 40.80% - Heavy

*In order to obtain the correct LCG, one weight had to be supported about 4" aft of the stern. This was accomplished with the use of an aluminum bracket.

SHAFT ANGLE The Shaft Angle of these models was relatively high at 11.9°. Location of the shaft line on the Webb model was 2.355" above the keel at station 5. The model was towed on the shaft line. In order to accomplish this, the dynamometer had to be raised on its slides and the vertical weight changed for each speed. Because of the high shaft angle, the dynamometer ran into its stops and it was necessary to lower the tank $2\frac{1}{2}$" to test at speeds above 6 fps. This was accomplished by drilling and tapping three $\frac{1}{2}$" holes in the overflow pipe of the tank. Brass plugs are used when the tank is filled to its normal level. Figure 1 shows the model rigged for testing.

TRIM GAUGES The trim gauges were located near stations 0 and 10 with a base length of 34.0". The vertical height of the dynamometer was adjusted at each speed to agree with the forward rise reading. The arms of the trim gauges were adjusted before testing to be vertical at the center scale reading.

TIME BETWEEN RUNS A period of 1.5 min. from time of return of model until the start of a new run was used. A return speed of 1.16 fps. was the maximum that could be used without flooding the stern.

SPEED RANGE The model was tested from speeds of 0 to 12.7 fps. This corresponds to a maximum speed-length of 4.5.

WETTED LENGTHS The following points were recorded:

(1) Fwd point on keel

(2) Fwd point on chine (spray)

(3) Waterplane intersection with chine

(4) Secondary point on chine

(5) Wetted point at transom

A sketch illustrating these points is included as figure 2.

DYNAMOMETER The dynamometer is a spring balance type with an oil filled dashpot. With the light spring, resistances up to .5# could be accurately obtained to three significant figures. Above this a larger spring was used for the ranges of .5 to 1.5#. The springs were calibrated before each use.

GENERAL NOTES With the model in the water and attached to the dynamometer, the trim gauges were attached and set to a zero reading. The vertical arms of the trim gauges were lined up with a plumb bob while the dynamometer was held at the middle

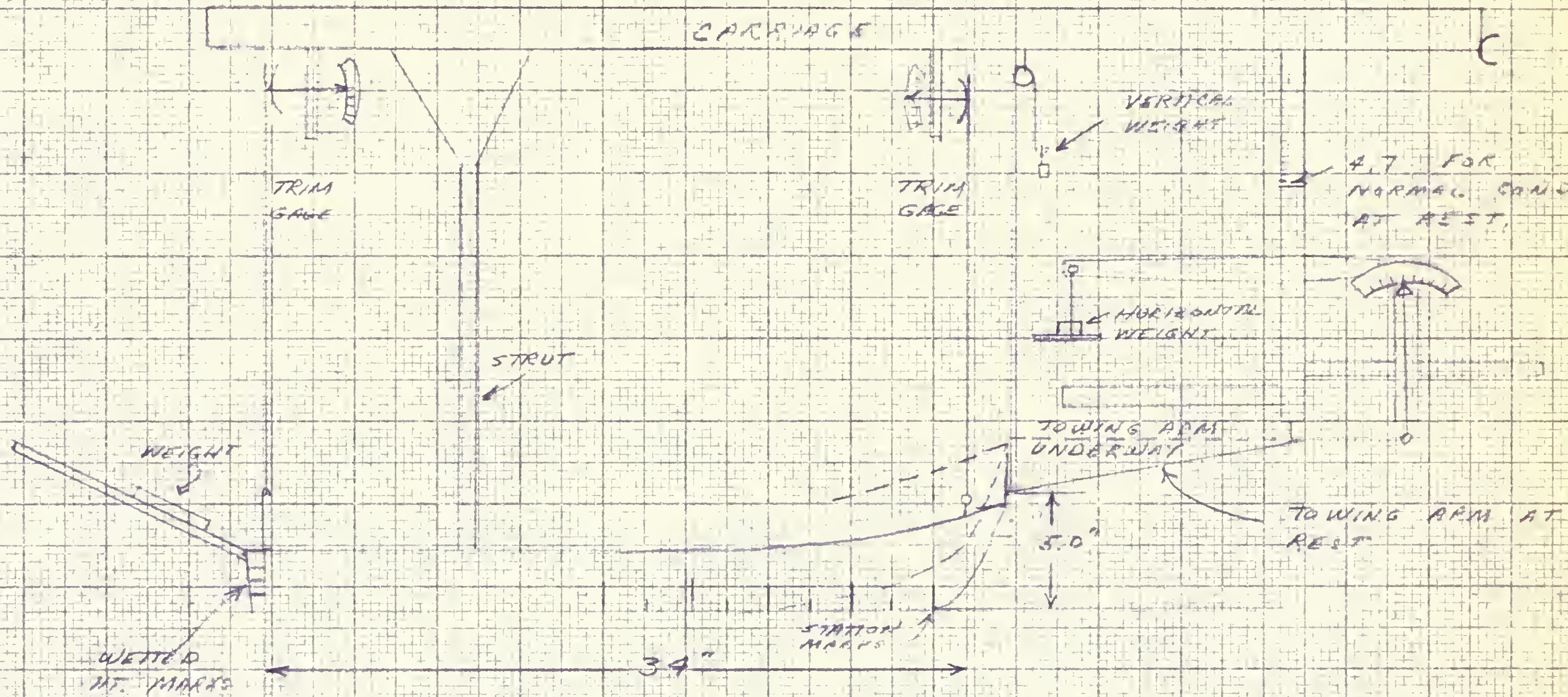
of the scale. The height of the towing point above water was used as a reference for THE vertical height.

Because of the high trim of this model, the dynamometer had to be checked for the range of scale readings at each of the higher speeds. The strut had to be set to protect the dynamometer in the at rest condition. As speed increased, the model trimmed and the strut hit the bracket sooner and restricted total movement of pointer on the scale. This problem was relieved above a speed length of 3.5 when the stern began to rise more.

On the first run at any speed the trim readings, dynamometer scale, and time were read. With the fwd rise, the dynamometer height was set and from the trim readings the vertical force calculated and placed on pulley. In succeeding runs, all wetted lengths were read and corrections made as necessary in horizontal weights, vertical weights, dynamometer height, and speed settings.

During high speed testing, the acceleration switch had to be switched to low before the return runs to prevent flooding the model. The braking switch was kept on maximum braking.

With heavy spring, an additional check on scale reading WAS obtained by adding or removing .01# on pan. With the light spring a slight change in speed setting will indicate whether THE previous reading was good. Observing position of towing strut will also indicate whether the reading is good or not.



MODEL AT REST, NORMAL CONDITION

WATER LEVEL NORMAL

FIGURE 1

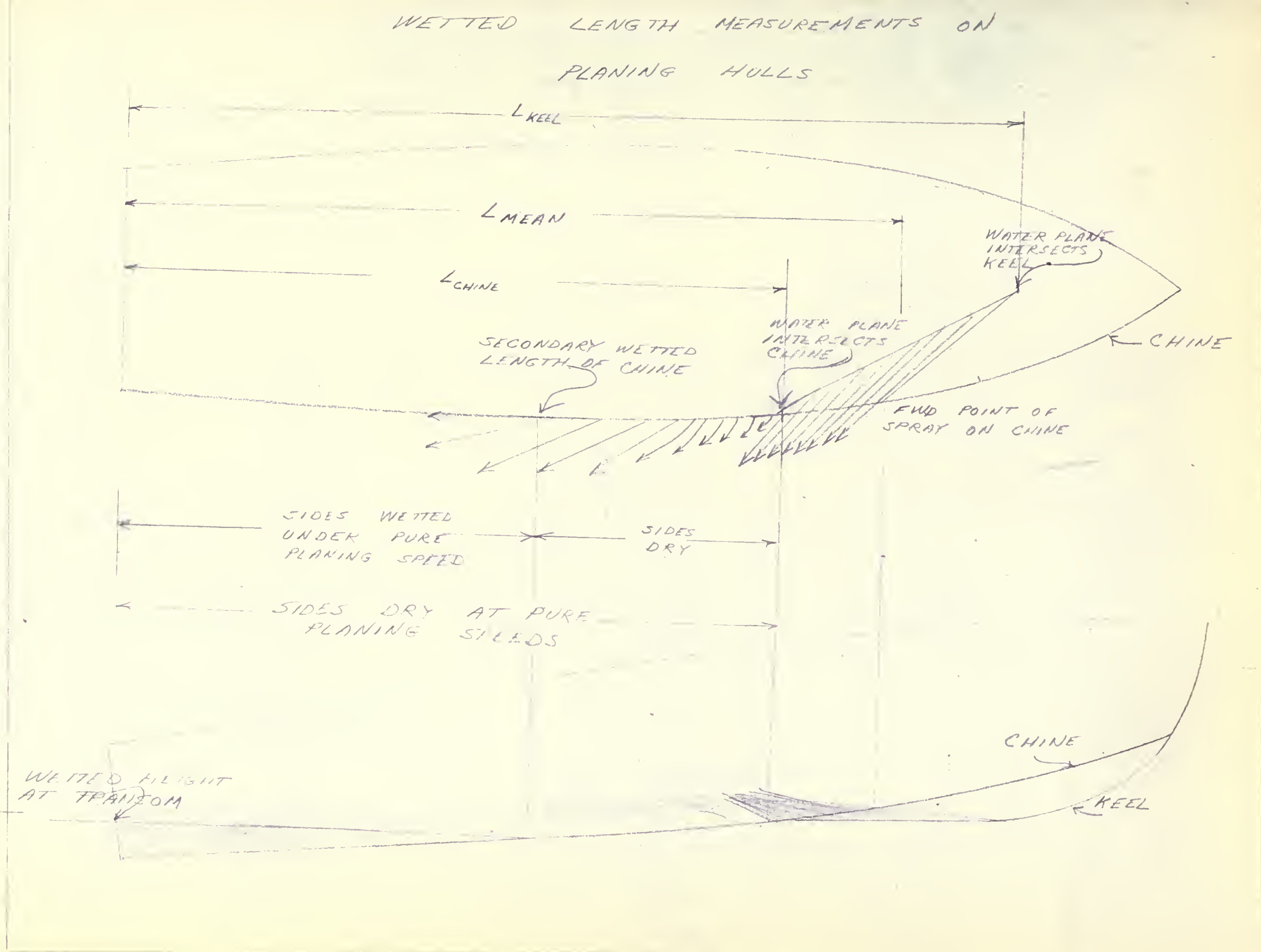

WETTED LENGTH MEASUREMENTS ON
PLANING HULLS
L KEEL
L MEAN
L CHINE
WATER PLANE INTERSECTS KEEL
WATER PLANE INTERSECTS CHINE
CHINE
SECONDARY WETTED LENGTH OF CHINE
FWD POINT OF SPRAY ON CHINE
SIDES WETTED UNDER PURE PLANING SPEED
SIDES DRY
SIDES DRY AT PURE PLANING SPEEDS
CHINE
KEEL
WETTED HEIGHT AT TRANSOM

FIGURE 2

TURBULENCE STIMULATION

The smallest and next to largest DTMB models were tested with and without a turbulence strut. The size of the strut used in these tests is unknown to the authors. The results showed no noticeable differences. The small model constructed at Webb was tested with various stimulators including a single strut, 3 struts, and numerous systems of pins.

First tests of the bare hull of the small model at Webb indicated the need of some sort of turbulence stimulator at the lower speed ranges. The resistance of the model was not reproducible. These initial bare hull points were checked and rechecked over a period of seven days. Initially it was felt that inability to reproduce initial results may have been due to faulty test technique by the authors. It was eventually decided that stimulation was required to insure consistent test results.

Stimulator tests were begun the early part of April, but the working speed range was limited to speeds below 9 fps. The reason for this restriction was due to the limited vertical rise of the dynamometer to maintain the towing arm horizontal during the test run. Although means for lowering the tank level were available, other tests were being conducted which restricted utilizing this means of extending the dynamometer height.

The primary source of the methods of attack for the solution of the turbulence stimulation problem was reference 4.

The following test techniques were used throughout the stimulator test runs. Attempts were made to keep the turbulence level of the tank as high as possible. The reverse speed of the model was kept as high as possible. In the case of the model tested, the reverse speed used was 1.16 fps. This speed was limited because of the extremely low freeboard at the stern. If the model were run at a higher reverse speed, swamping would occur. The time interval between runs was kept to the lowest value which would still allow the waves in the tank to dampen out. This interval was two minutes at the beginning of the test period but was later reduced to 1.5 minutes. Before testing, four high and low speed runs were made. Results of these runs were not recorded.

To insure a proper turbulence level in the tank, a stick was pulled through the water before testing. The limited speed range available from 1.25 to 8 fps. corresponds to Reynolds numbers from 3.4×10^5 to 1.5×10^6. These Reynolds numbers are based on the mean wetted length. Trim indicators were adjusted to zero for each run. This was an error in technique since it results in a changing reference for trim measurements. Since the authors were looking for comparable changes, this technique was used throughout the remainder of the stimulator tests.

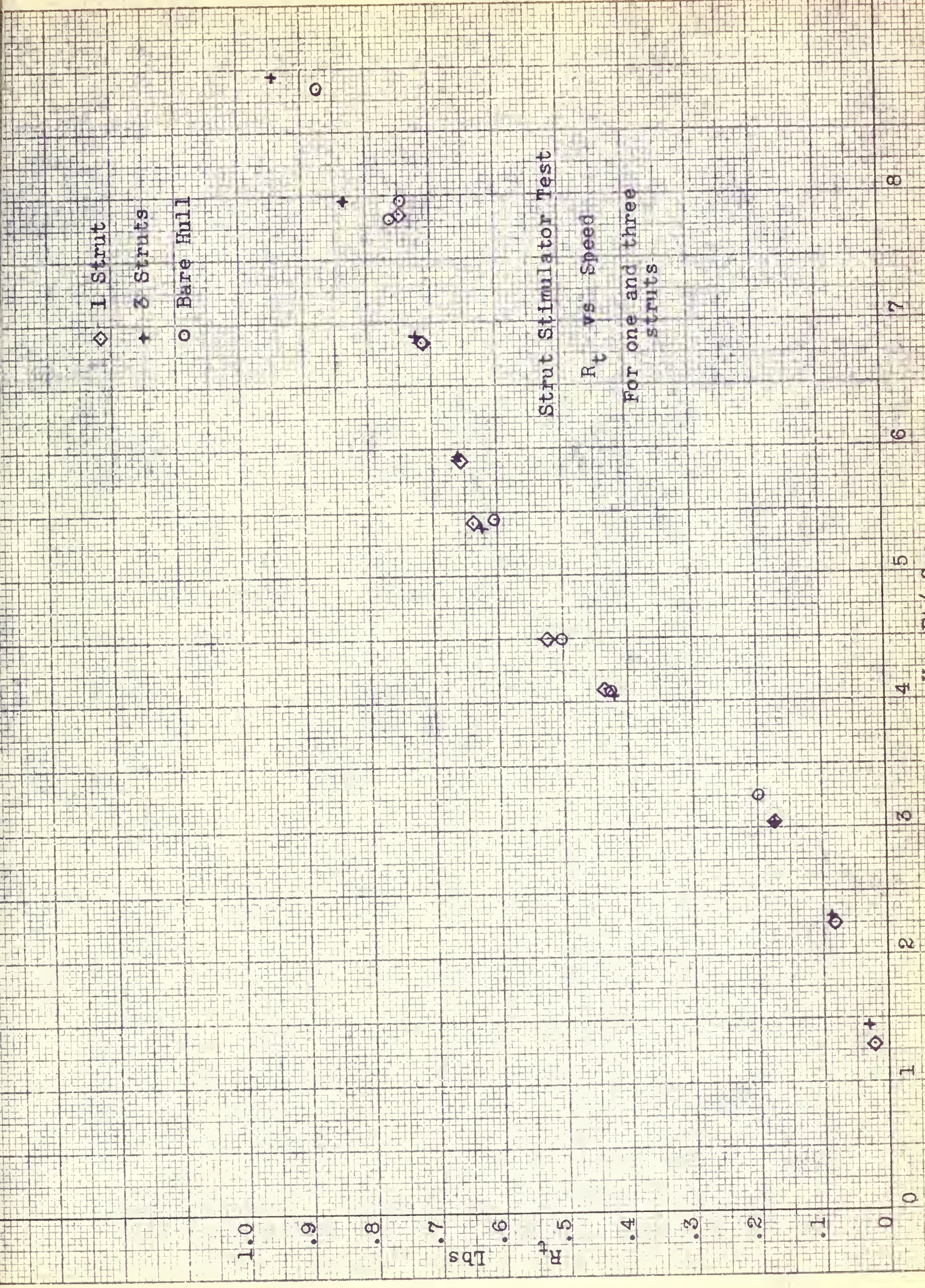
Since a total resistance coefficient vs. speed-length plot was not practicable during testing, a rough plot of total resistance vs. speed was maintained. Another technique used, was to test the stimulators at the identical speeds at which the

bare hull tests were conducted. This method then would show any direct difference between bare and stimulator resistance readings, wetted lengths, and model trims. During the stimulator tests over the speed range from 1.15 to 8 fps., no changes in trim or wetted lengths from bare hull tests were detectable. All tests were conducted with the model at normal displacement.

TEST WITH STRUTS The first stimulator tests were conducted utilizing a .04" diameter strut 4" from the stem of the model. These tests showed an increase in resistance over bare hull up to speed of approximately 6 fps. The plots became coincident with the bare hull up to 8 fps. as shown in Figure 3. This trend at the higher speed was attributed to the increased distance between the strut and intersection of the water surface with the keel of the model due to the increasing trim.

The next stimulator tested was a triple strut with a center strut of .062" and two struts at the quarter beam points of .04" diameter. At speeds below 3 fps., the resistance of the model tested with the triple strut fell below the bare hull resistance at corresponding speeds. This negative trend was attributed to the wake effect of the stimulator at the lower speeds due to proximity of the strut to the stem, which is also shown in Figure 3. This terminated the strut phase of testing.

The authors felt that a stimulator removed from the hull was unsatisfactory because it would require a constant shifting to a new position for each speed tested. This would be necessary to keep the distance constant between the strut and the intersection of the water surface with the keel and chine of the model at running speeds.



◇ 1 Strut
+ 3 Struts
○ Bare Hull
Strut Stimulator Test
R_t vs Speed
For one and three struts
V Ft/ Sec
R_t Lbs
0
1
2
3
4
5
6
7
8
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0

FIGURE 3

PINS At Webb Institute, the use of relatively large pins, as a turbulent stimulator on Trawler Hull forms, have proven very successful. Considerably smaller ones, size S.C., rust-proof brass silk pins of .025 diameter with heads removed were used as stimulators in these tests. These were placed at a distance of 4" from the intersection of the water surface with the keel and chine at a speed that was the mean of the speed range to be investigated.

The distance of 4" was based on the successful results obtained in Reference 4. This distance was determined to be most effective in producing a transition from a laminar to a fully turbulent condition. The pin resistance may be large, but it is believed that it is compensated by the laminar flow that exists before the pins. The resulting configuration is an inverted vee on the hull bottom looking from the stern forward. As pins were removed during this phase of testing, the holes were filled with wax.

TEST I The initial speed selected as a mean reference point for pin location was 6 fps. The intersection of the waterplane with the keel and chine at this speed was 1.5 and 3.7. The pins were located at ½" behind station 2 on the centerline, and ½" behind station 5, out of 10 stations on the chine. This arrangement is shown in Figure 4.

The initial height of pins was .1" with a transverse spacing of ½". This resulted in an average increase in resistance of 3% from 5 fps. to 8 fps. In the speed range below 4 fps., the resistance plots were coincident with the bare hull test plot. This tended to indicate a fully turbulent

condition at the pins, but the intersection of the water plane with the keel and chine had shifted forward and the distance to the pins was 3" greater than the 4" spacing at 2 fps. Test results for this test are shown in Figure 5.

TEST II At this point the authors decided to install a second row of pins at station 1.2 on the keel and station 3.8 on the chine with a pin height of .1" and with a transverse spacing of $\frac{1}{2}$". This was done to reach a fully turbulent condition at the lower speeds. With the pin configuration outlined above, the model was retested. As the speeds increased, the forward row of pins would be lifted out of the water and leave the latter row immersed.

Over the speed range from 2 to 4 fps., the mean average increase of R_t was 4% above the bare hull. Over the speed range from 5 to 7 fps., this mean increase was 5.6%. During this series of tests, the dynamometer readings became very erratic. This effect was attributed to some of the pins in the first row alternately going in and out of the spray area. This arrangement and the results of the tests are shown in Figures 6 and 7.

TEST III In the continuation of the series of pin stimulator tests, the second row of pins was increased in number resulting in a $\frac{1}{4}$" spacing and at the same time the pin height was reduced to .05. Plots of Tests II and III were coincident over the entire speed range from 1.15 to 8 fps. Pin locations for Tests III and IV are shown in Figure 8 and results in Figure 9.

TEST IV In this test series, the first row was reduced to

a height of .05" with no change in pin spacing. All points were again coincident with Tests II and III.

Four tests were conducted using a combination of pins and strut stimulators but these were omitted in the final analysis because the resistances measured indicated a wake effect at the lower speeds and coincident plots with Test IV at speeds from 3 to 8 fps. Results are shown in Figure 10.

At this time the authors felt that a satisfactory arrangement over the entire speed range could be effected using a standard pin height of .05 in a Christmas Tree arrangement with a pin spacing of $\frac{1}{4}$".

This final arrangement was a compromise to avoid erratic dynamometer readings as the pins in the first and second row near the chine caused a changing flow condition and is shown in Figure 11. The authors felt that with this final arrangement the pins aft of the effective stimulator row would not contribute to increased drag because they were located in a region that was over stimulated, as stated in reference 4. "Provided that the initial stimulation is of the correct order of magnitude, an increase in stimulator drag is offset by a decrease in frictional resistance (due to over stimulation) and the two effects tend to cancel each other." This effect was obtained in Tests II and III. As an example: With the final pin arrangement at speeds between 1 to 3 fps., the first row is the effective stimulator. Although rows two and three were completely immersed, no increase over the initial tests with just the first row of pins on the model was noted. The authors believe this effect is due to rows two and three

causing over stimulation and the two effects of decrease in frictional resistance tend to cancel the effect of increased stimulator drag of row two and three.

Based on the bare hull resistance plot and the wetted length obtained during these tests, the speeds of 3, 6 and 11 fps. were used to determine the pin location for the final tests.

The pins near the chine of the first two rows were removed to avoid erratic dynamometer readings because of their effect on flow pattern as they came in and out of the spray area. Final tests of both the normal and heavy displacement were made with the configuration shown in Figure 11. Plots of R_t, S_t, and L_m are shown in Figures 14-19 contained in the Section on Model Test Results.

Based on the final test results, the following method of testing planing hulls is suggested:

1. Test the bare hull model over its entire speed range recording R_t, wetted lengths and change in trim.
2. Depending on the shape of the resistance curve, divide the speed range into three segments.
3. For each of the three segments select the mean speed and obtain wetted intersections of keel and chine for these speeds.
4. Locate the rows of pins 4" ahead of a line through the intersections at the keel and the chine.
5. Retest the model.

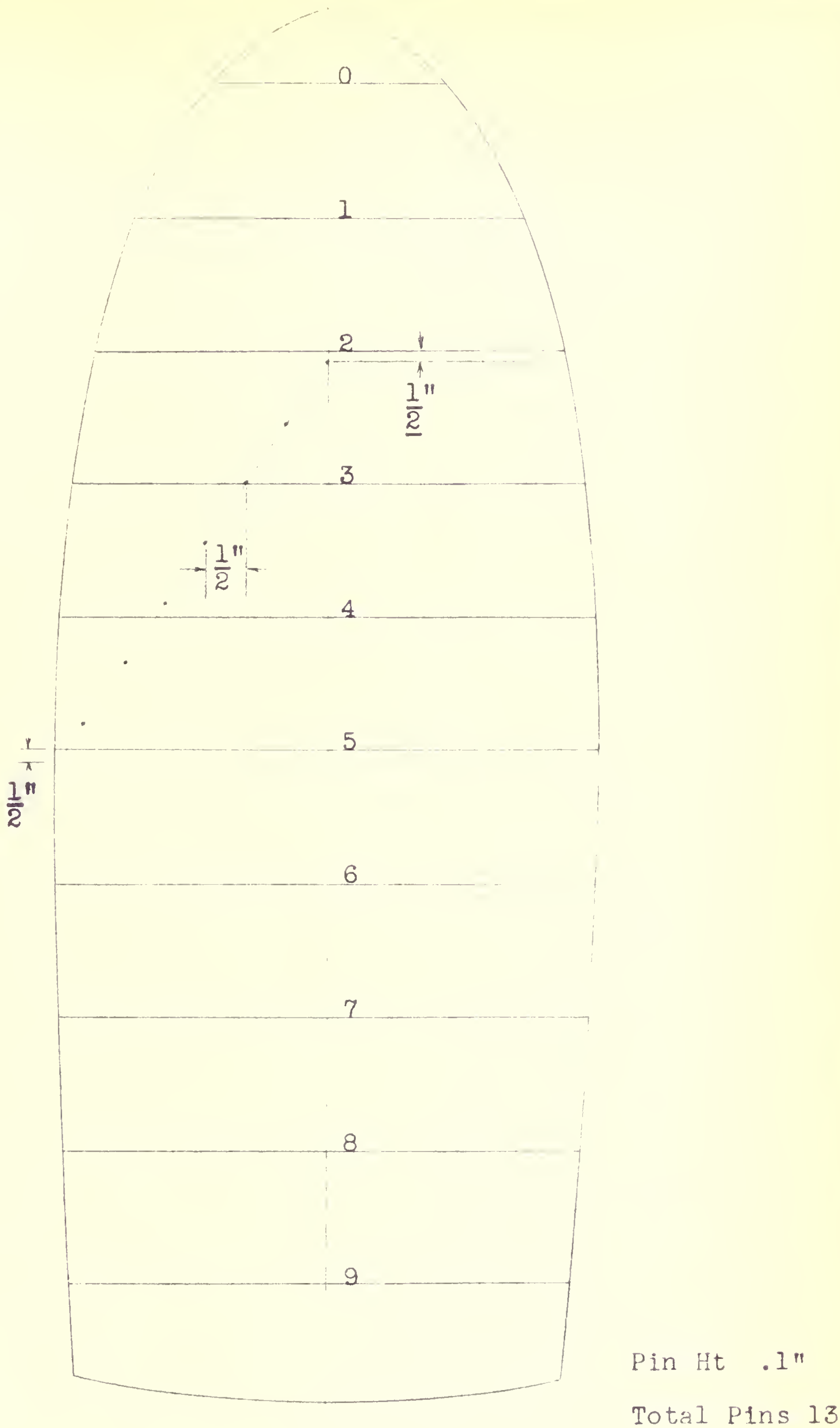


FIGURE NO.4 PIN STIMULATOR LOCATION TEST I

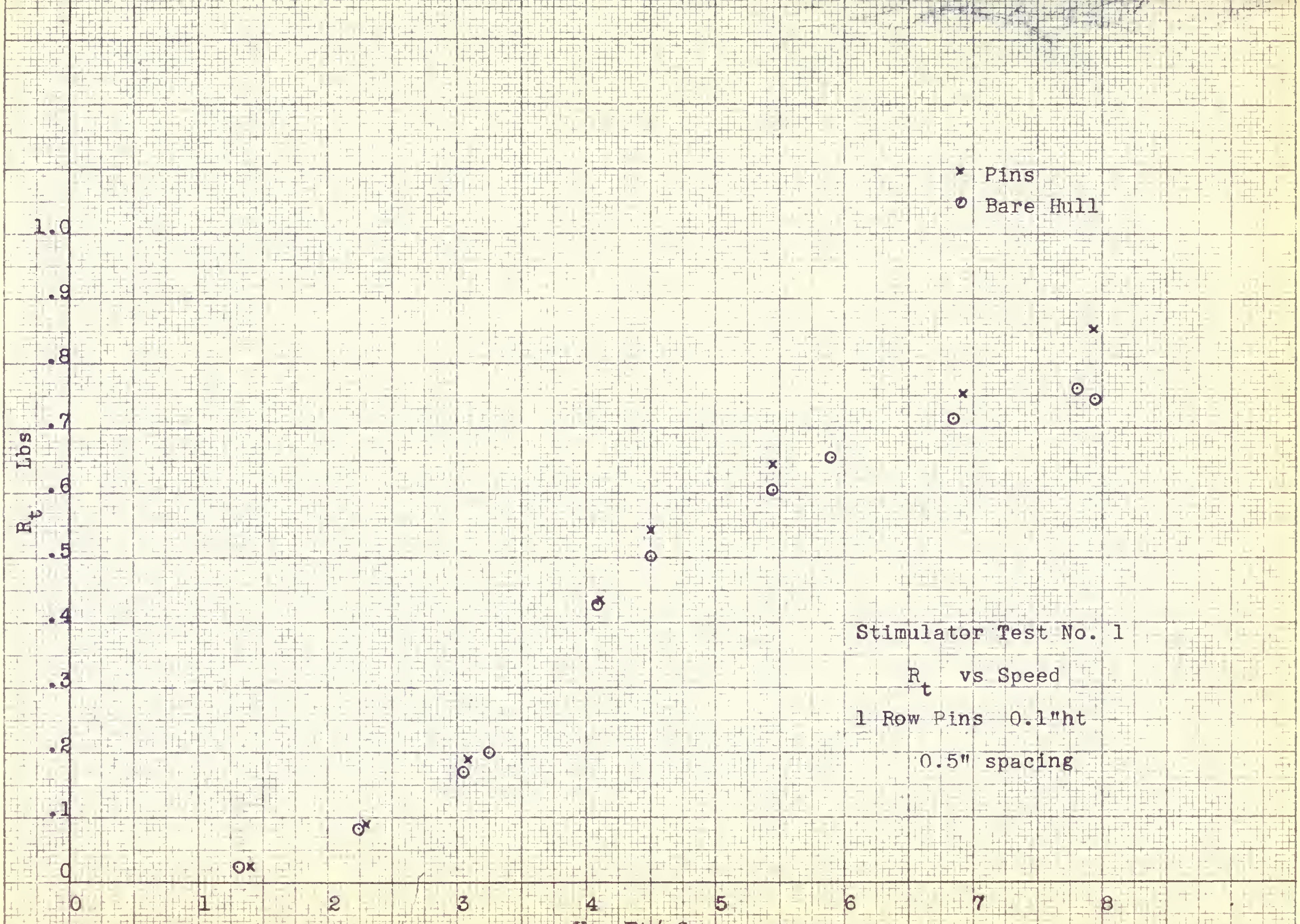

Pins
Bare Hull
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
R_t Lbs
0
1
2
3
4
5
6
7
8
V Ft/ Sec
Stimulator Test No. 1
R_t vs Speed
1 Row Pins 0.1"ht
0.5" spacing

FIGURE 5

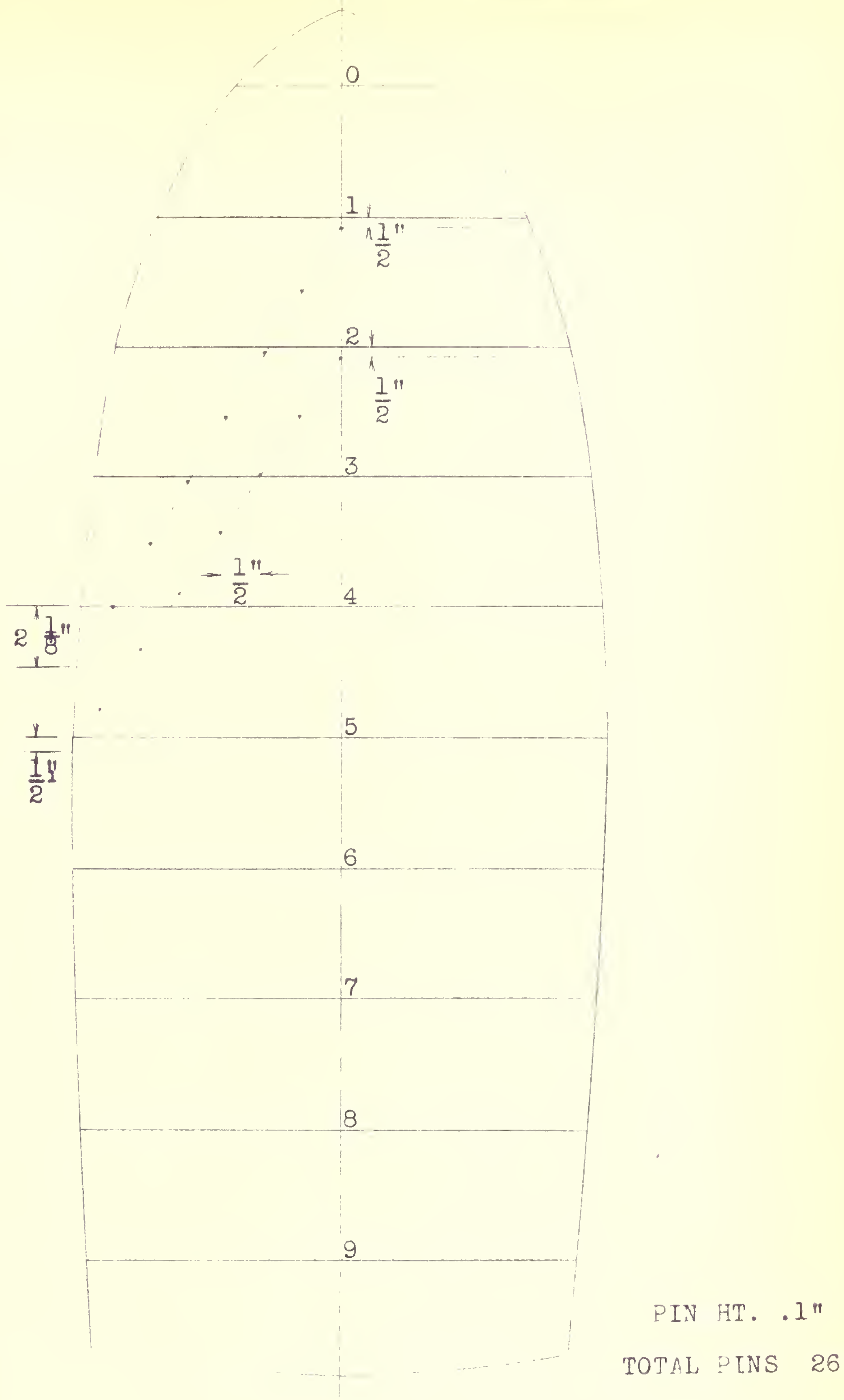
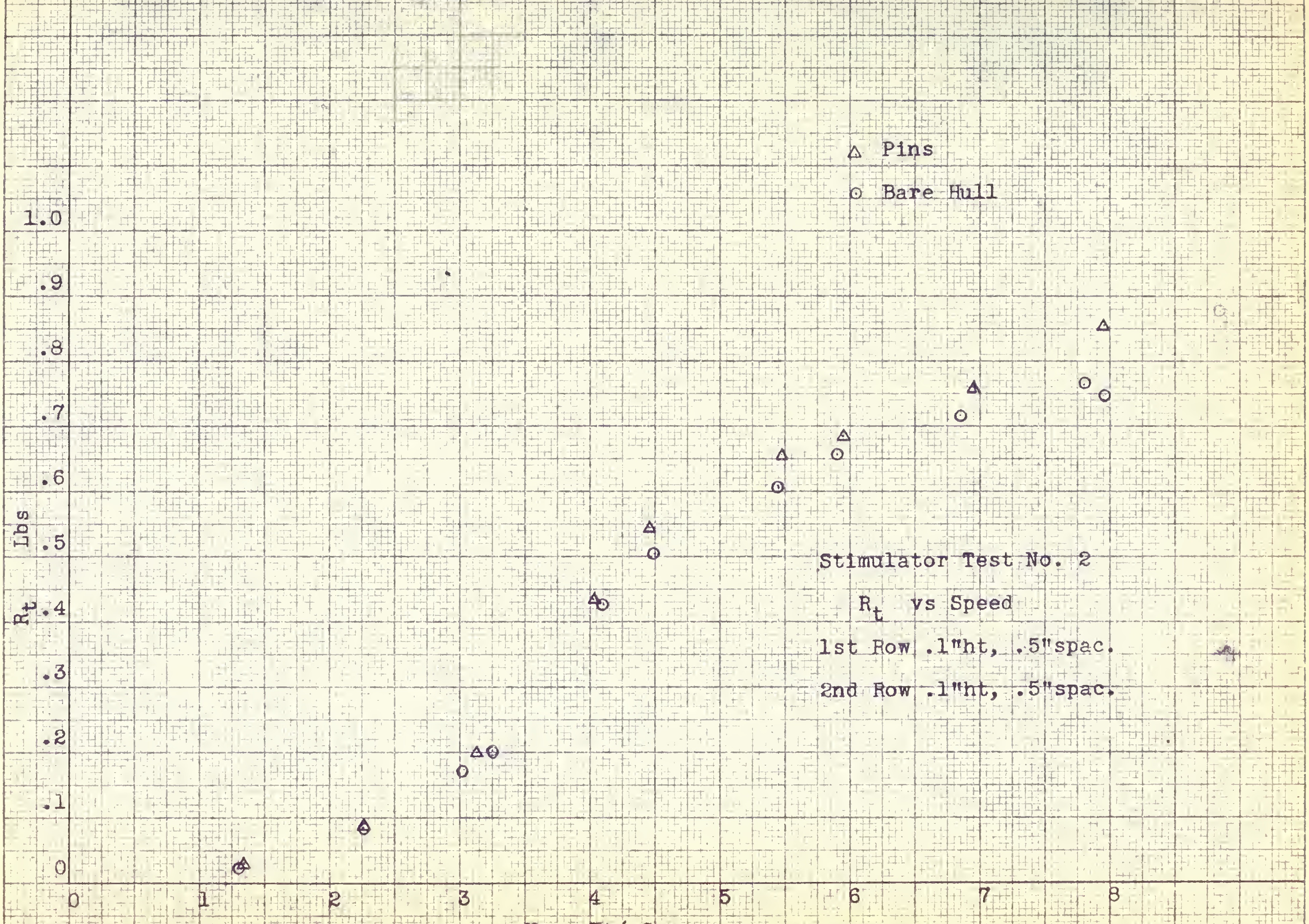
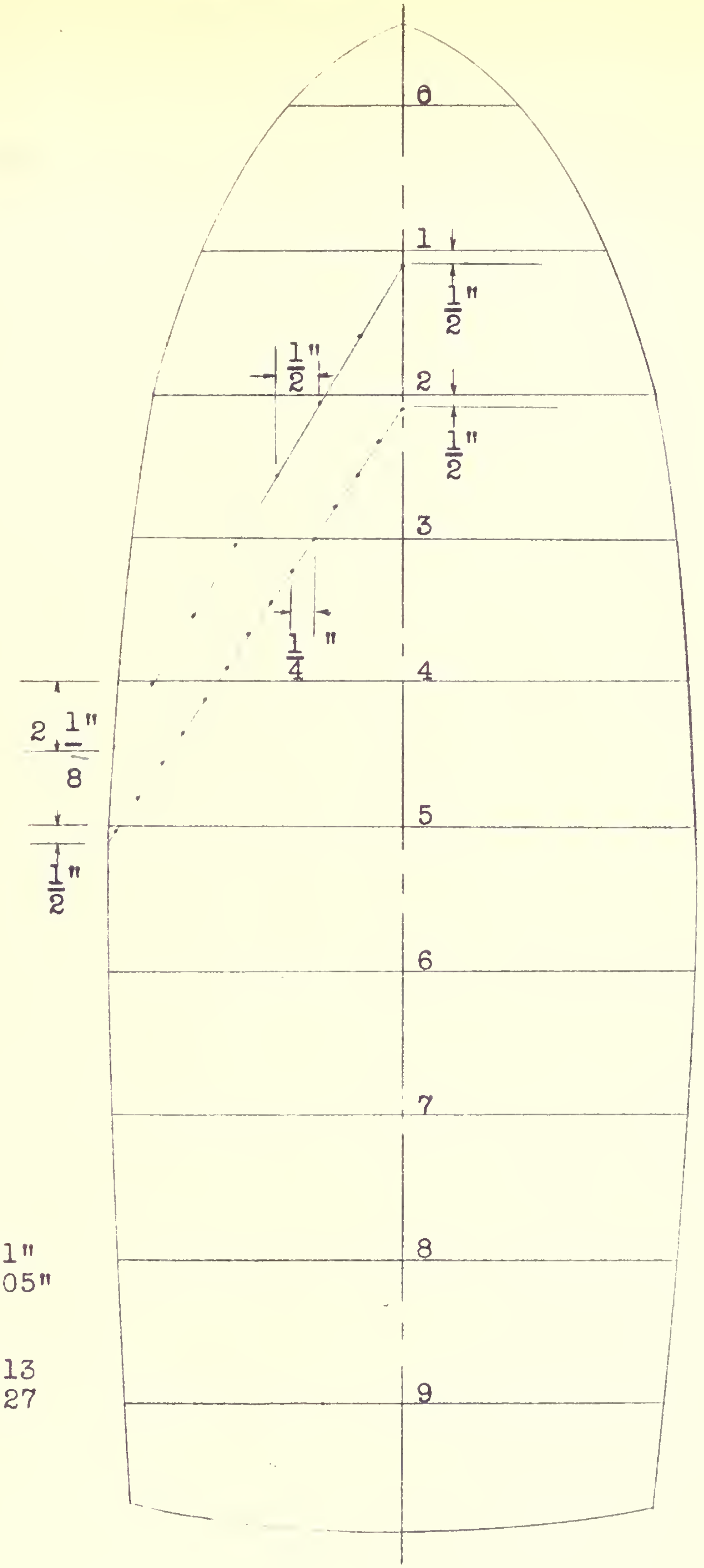


FIGURE NO. 6 PIN STIMULATOR LOCATION TEST NO. II



△ Pins
⊙ Bare Hull
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
Lbs
R_t
0
1
2
3
4
5
6
7
8
V Ft/ Sec
Stimulator Test No. 2
R_t vs Speed
1st Row .1"ht, .5"spac.
2nd Row .1"ht, .5"spac.

FIGURE 7



TEST III

Pin Height
Row 1 - .1"
Row 2 - .05"

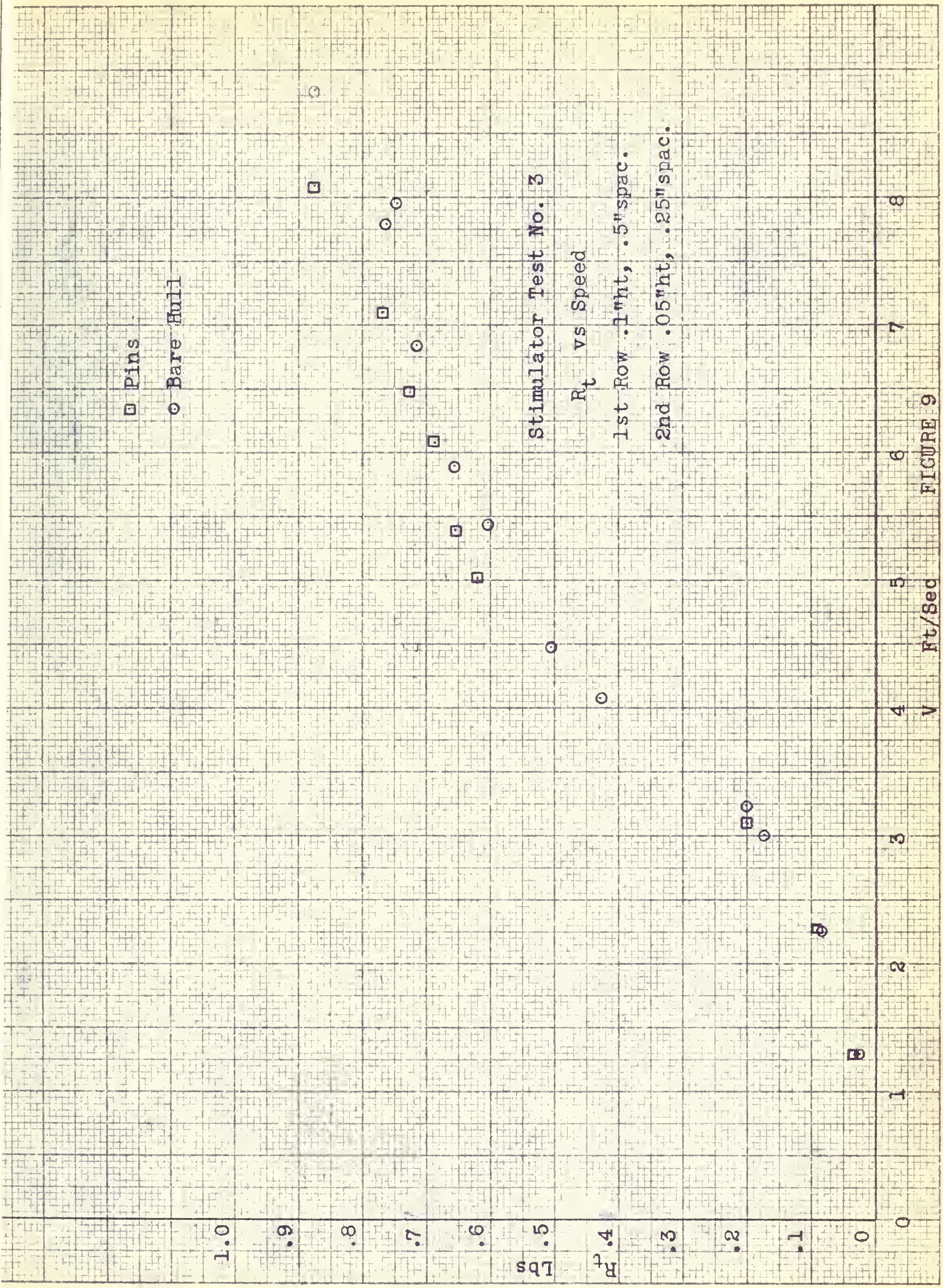
Total Pins
Row 1 - 13
Row 2 - 27

TEST IV

Pin Height
Both Rows - .05"

Total Pins - 40

FIGURE 8 PIN STIMULATOR LOCATION TESTS III & IV



□ Pins
⊙ Bare Hull
Stimulator Test No. 3
R_t vs Speed
1st Row .1"ht, .5"spac.
2nd Row .05"ht, .25"spac.
R_t Lbs
V Ft/Sec
FIGURE 9

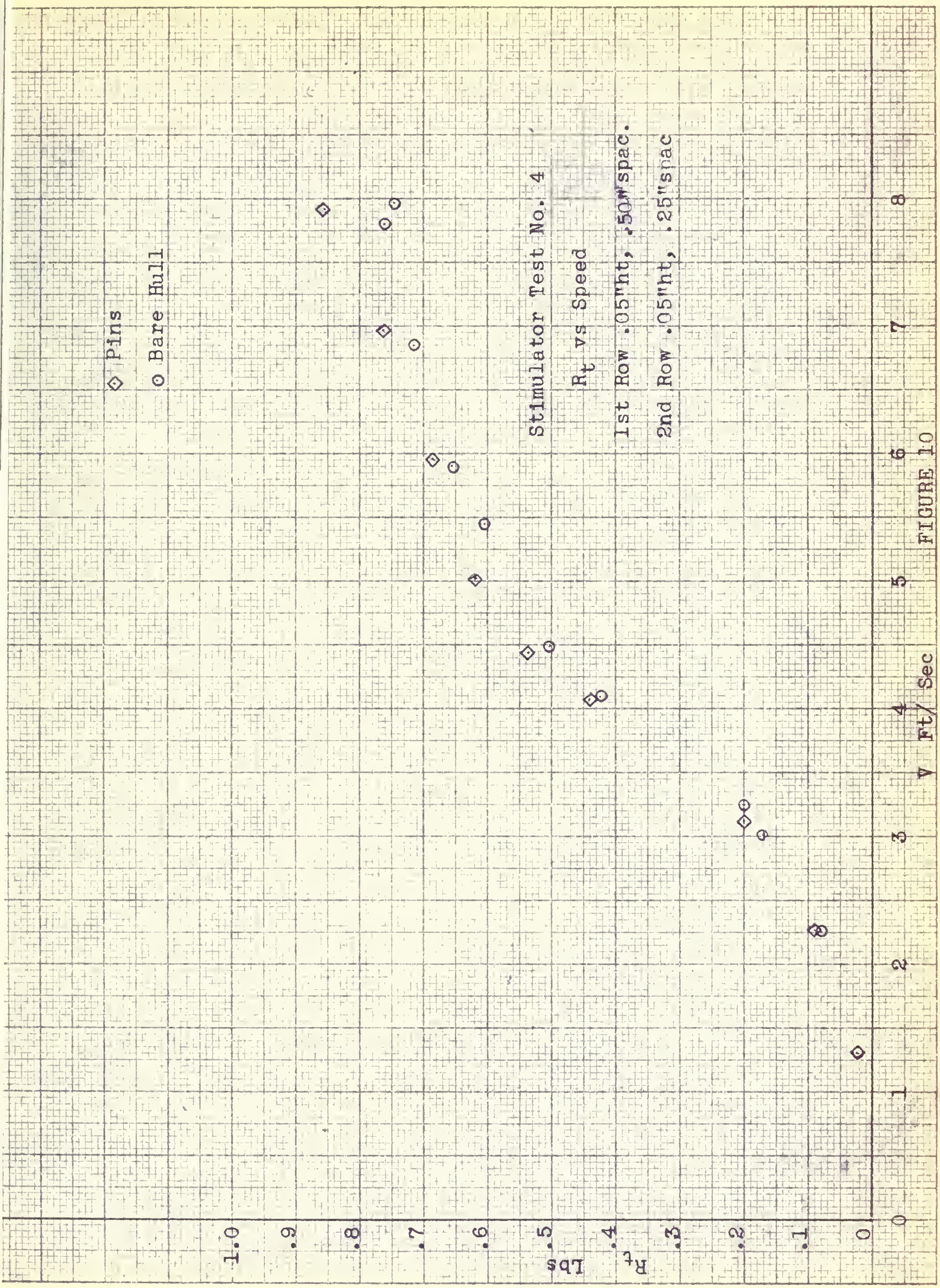
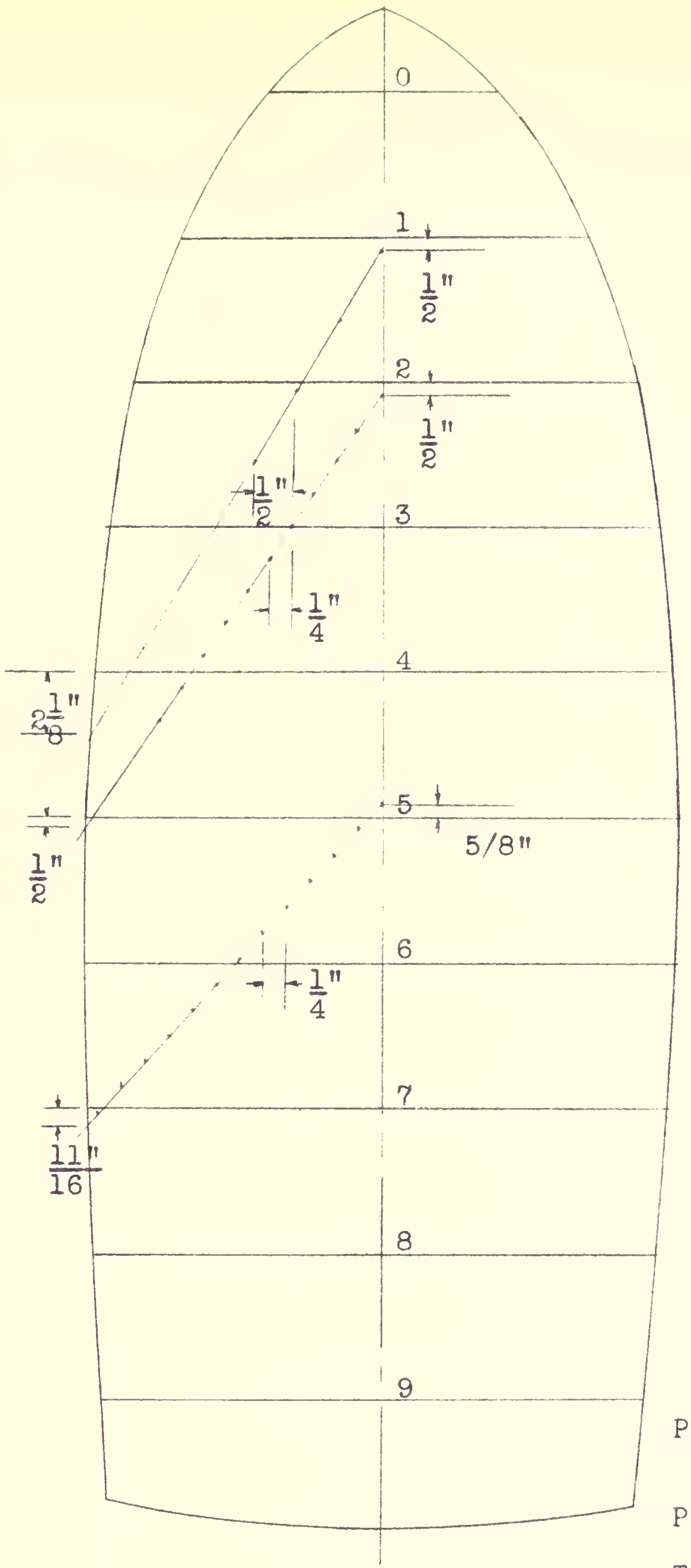

◇ Pins
⊙ Bare Hull
Stimulator Test No. 4
R_t vs Speed
1st Row .05"ht, .50"spac.
2nd Row .05"ht, .25"spac
V Ft/ Sec
R_t Lbs
0
1
2
3
4
5
6
7
8
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0

FIGURE 10



Pin spacing
Row 1 - 1/2"
Row 2 & 3 - 1/4"
Pin Height - .05"

Total Pins
Row 1 - 7
Row 2 - 21
Row 3 - 25

FIGURE 11 FINAL PIN LOCATION FOR STIMULATION OVER ENTIRE SPEED RANGE

TEST RESULTS

Only the results of the Webb model will be discussed in this section. Comparison of the results of all models is contained in the Discussion. In the analysis of the final bare and stimulated tests of the Webb model over the complete speed-length range, it is believed that the accuracy of the chine and keel readings was $\pm$ .05 station spacing. This error expanded would mean .05 x 90" = 4.50" error on the full size vessel. An error of this magnitude could cause a difference of $\pm$ 3 sq. ft. in the total surface out of a total of over 1,000 sq. ft. An error of .05 spacing on both the chine and keel reading results in a difference of $\pm$ 5 sq. ft. in total surface.

In the plot of change in trim (This is the change in trim from the still water condition to the speed of the model under consideration.) versus speed-length as shown in Figures 12 and 13, the plots of change in trim for both the bare and stimulated conditions in the normal displacements were coincident up to a speed-length of 1.75. From a speed-length of 1.75 to 2.90, the change in trim of the stimulated model was lower than the bare hull and the difference is at a maximum at a speed length of 2.5. This maximum difference in change of trim is .2 of a degree.

This same phenomena occured in the tests of the model at heavy displacement but it occured between speed-lengths of 2.5 and 3.75. The maximum difference in change of trim was $.25^{\circ}$

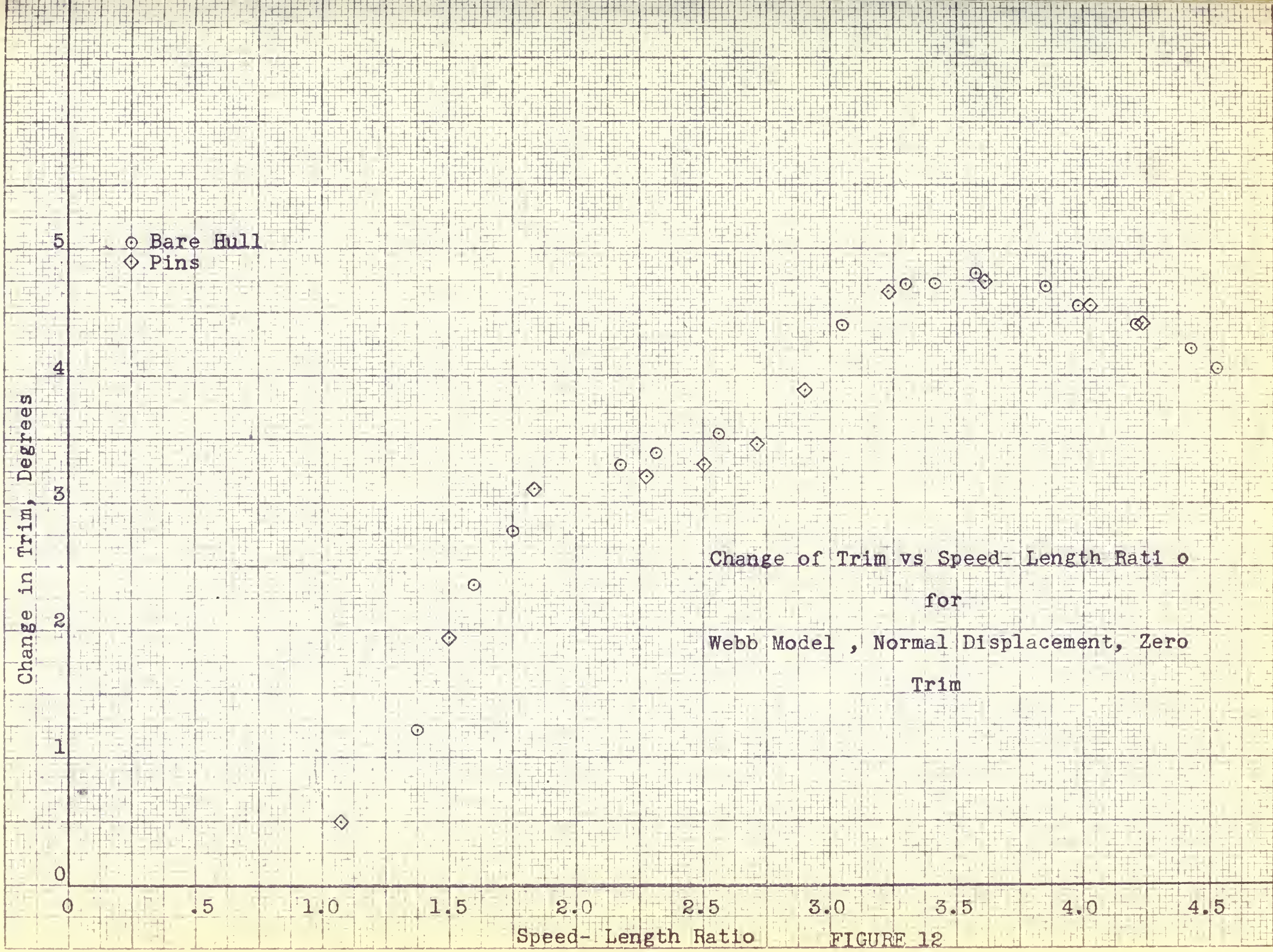
and occured at a speed-length of 3.0.

On the plots of mean length and wetted surface, as shown in Figures 14-17, there was a definite discontinuity in the mean length and total wetted surface at a speed-length of 1.5 for the model in normal displacement and at speed-length of 1.40 for the model in the heavy displacement. All speed-lengths are based on the length of the load waterline for the model in the normal condition and with zero trim. At the speed-lengths above 4.0, the plots of L_m and S_t begin to level off. This is to be expected in testing planing hulls since the hydrodynamic pressure center cannot move further aft than the location of the LCG. This places a restriction on the minimum L_m and S_t of the model without the model becoming unstable.

The maximum change of trim for the normal displacement occured at speed-length of 3.5 and the maximum change was 4.8° for the model in the normal condition. The maximum change was 5.1° and occured at a speed-length of 4.0 for the model at the heavy displacement and an initial trim of .9° x bow. This agrees with the plots in Reference 7 which show that the maximum trim of the model with LCG furthest aft should occur at the lower speed-length.

The total resistance for all test points for both the bare and stimulated conditions, ~~labeled Test 4 in the Stimulator Test Section~~, were plotted and are shown in Figures 18 and 19.

With turbulence stimulation, the Webb model showed an increase in resistance from 4 to 7% over the whole speed range for both the normal and heavy displacements.



Change of Trim vs Speed- Length Rati o
for
Webb Model , Normal Displacement, Zero
Trim

FIGURE 12

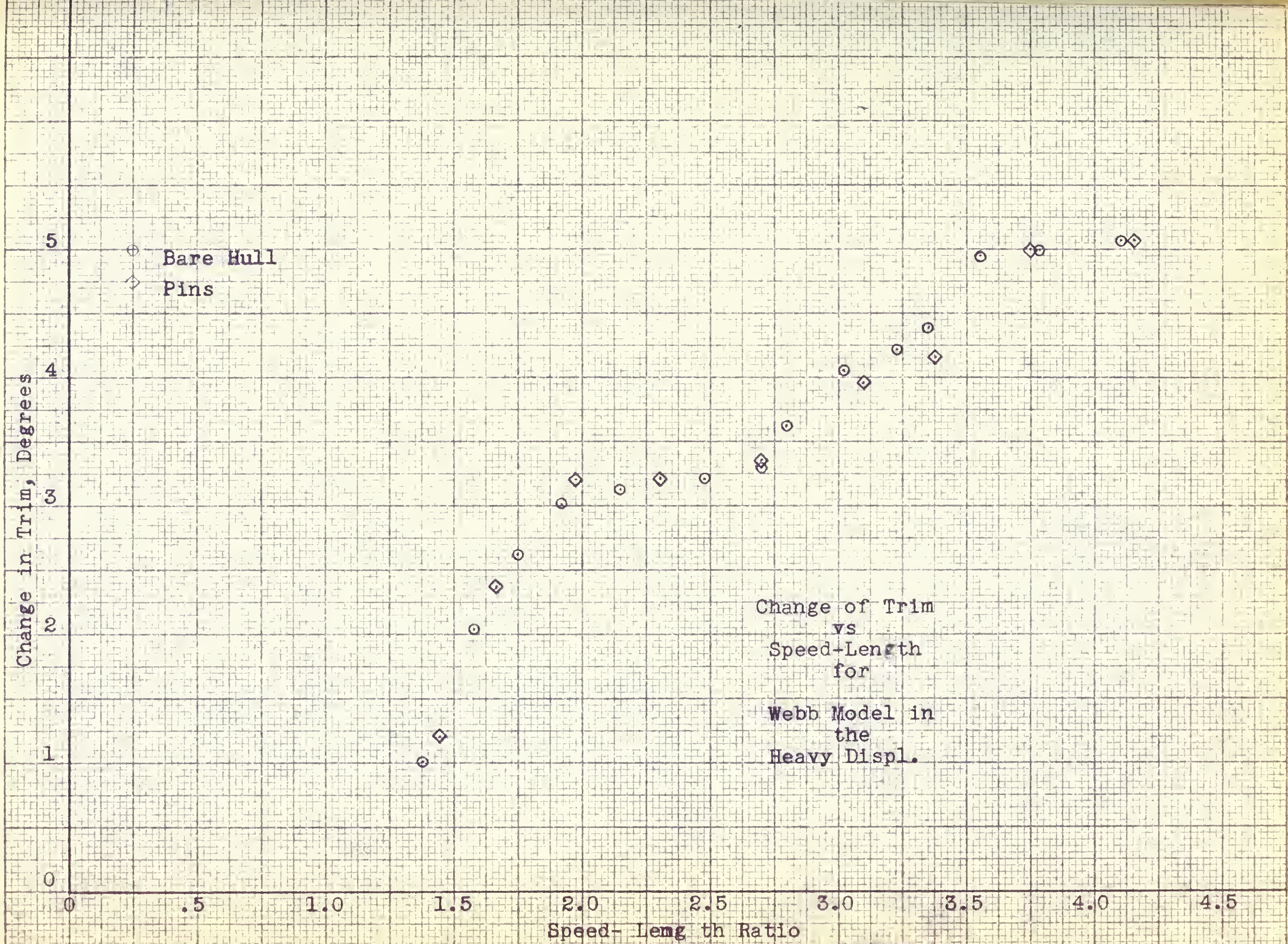
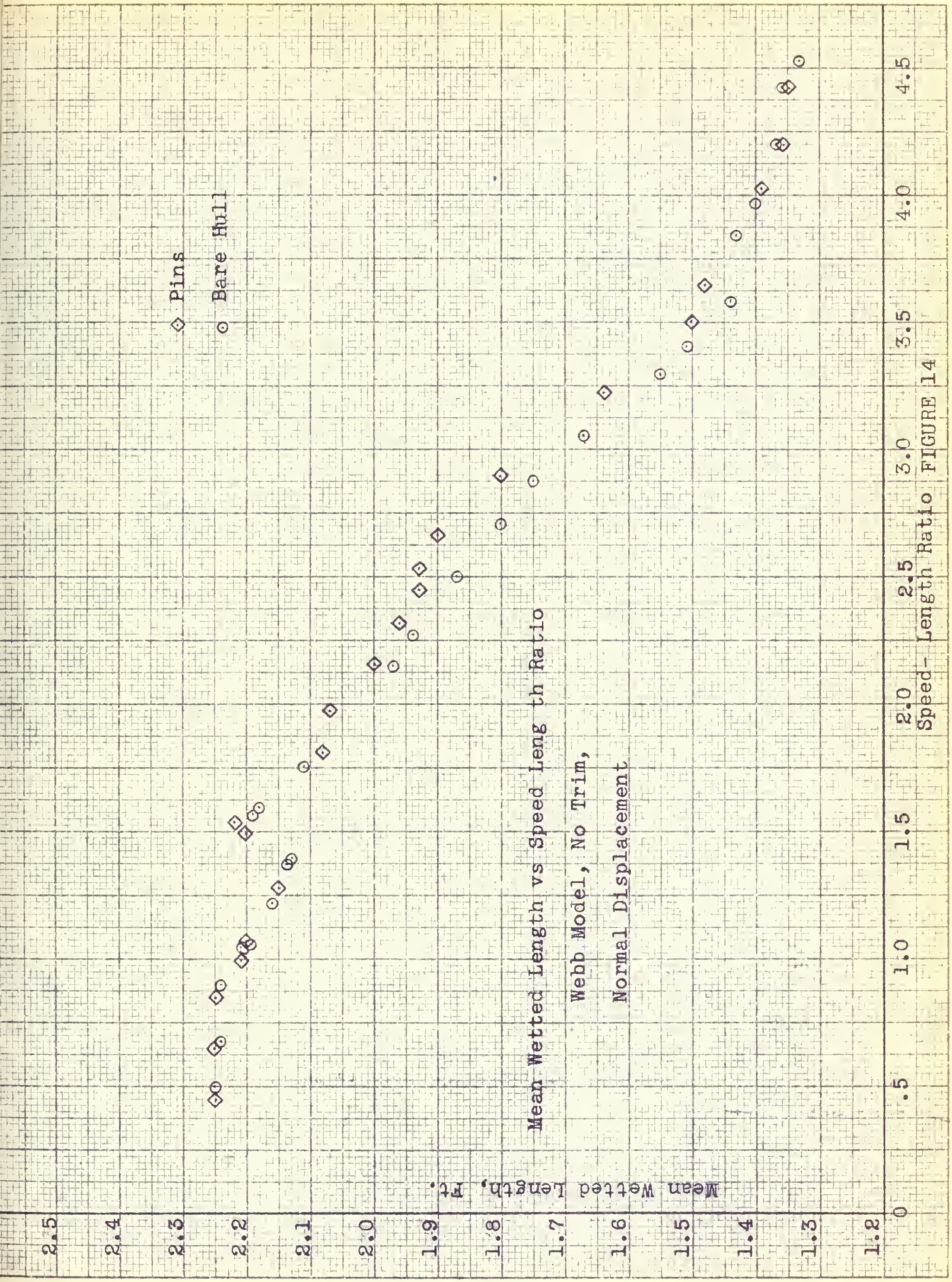
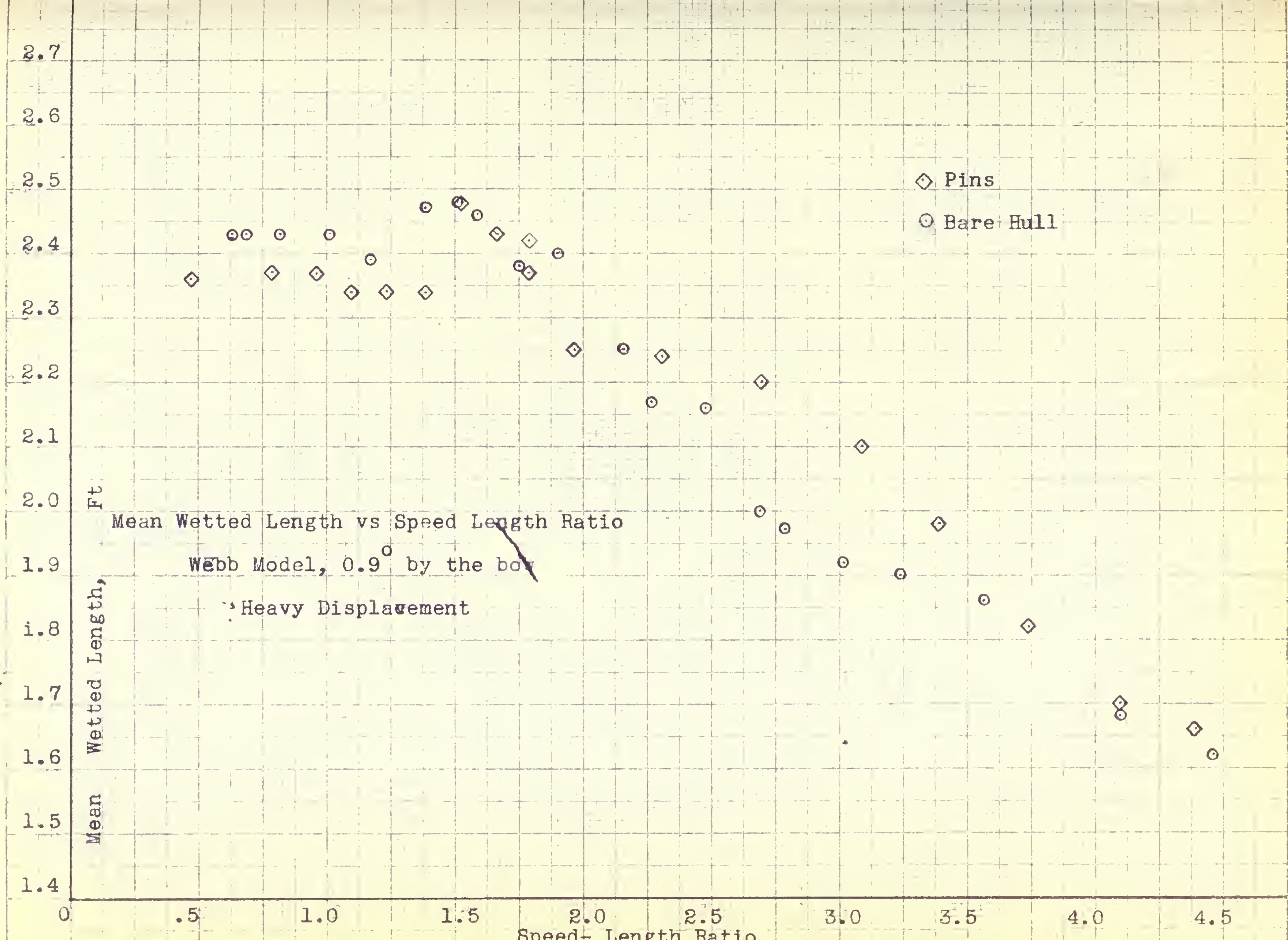

Bare Hull
Pins
Change in Trim, Degrees
0
1
2
3
4
5
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Speed- Lemg th Ratio
Change of Trim
vs
Speed-Length
for
Webb Model in
the
Heavy Displ.

FIGURE 13


Mean Wetted Length vs Speed Leng th Ratio
Webb Model, No Trim,
Normal Displacement
Pins
Bare Hull
Mean Wetted Length, Ft.
Speed- Length Ratio
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
FIGURE 14



Pins
Bare Hull
Mean Wetted Length vs Speed Length Ratio
Webb Model, 0.9° by the bow
Heavy Displacement
Mean Wetted Length, Ft
Speed- Length Ratio
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5

FIGURE 15

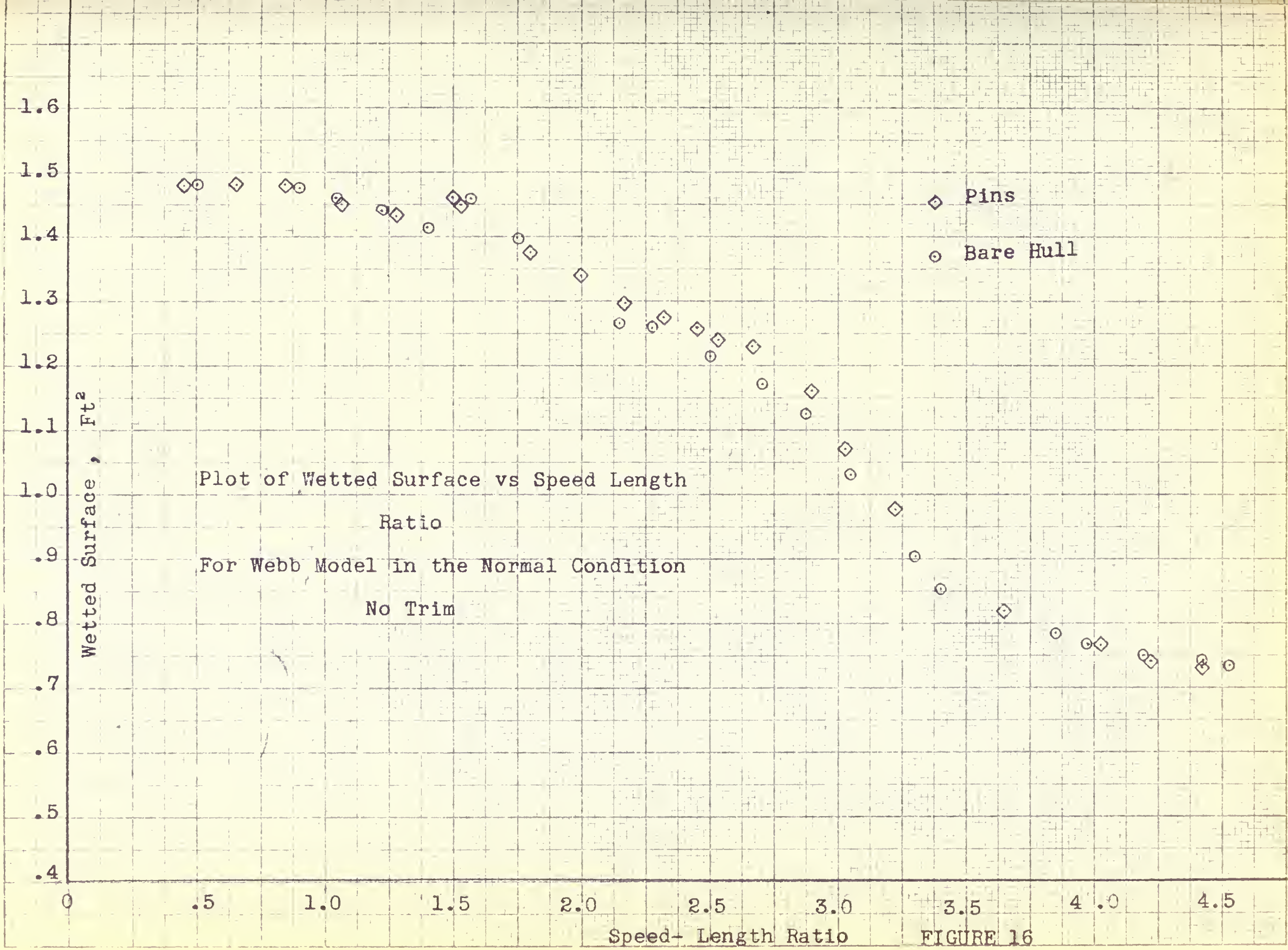

Pins
Bare Hull
Plot of Wetted Surface vs Speed Length
Ratio
For Webb Model in the Normal Condition
No Trim
Wetted Surface , Ft^2
Speed- Length Ratio
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5

FIGURE 16

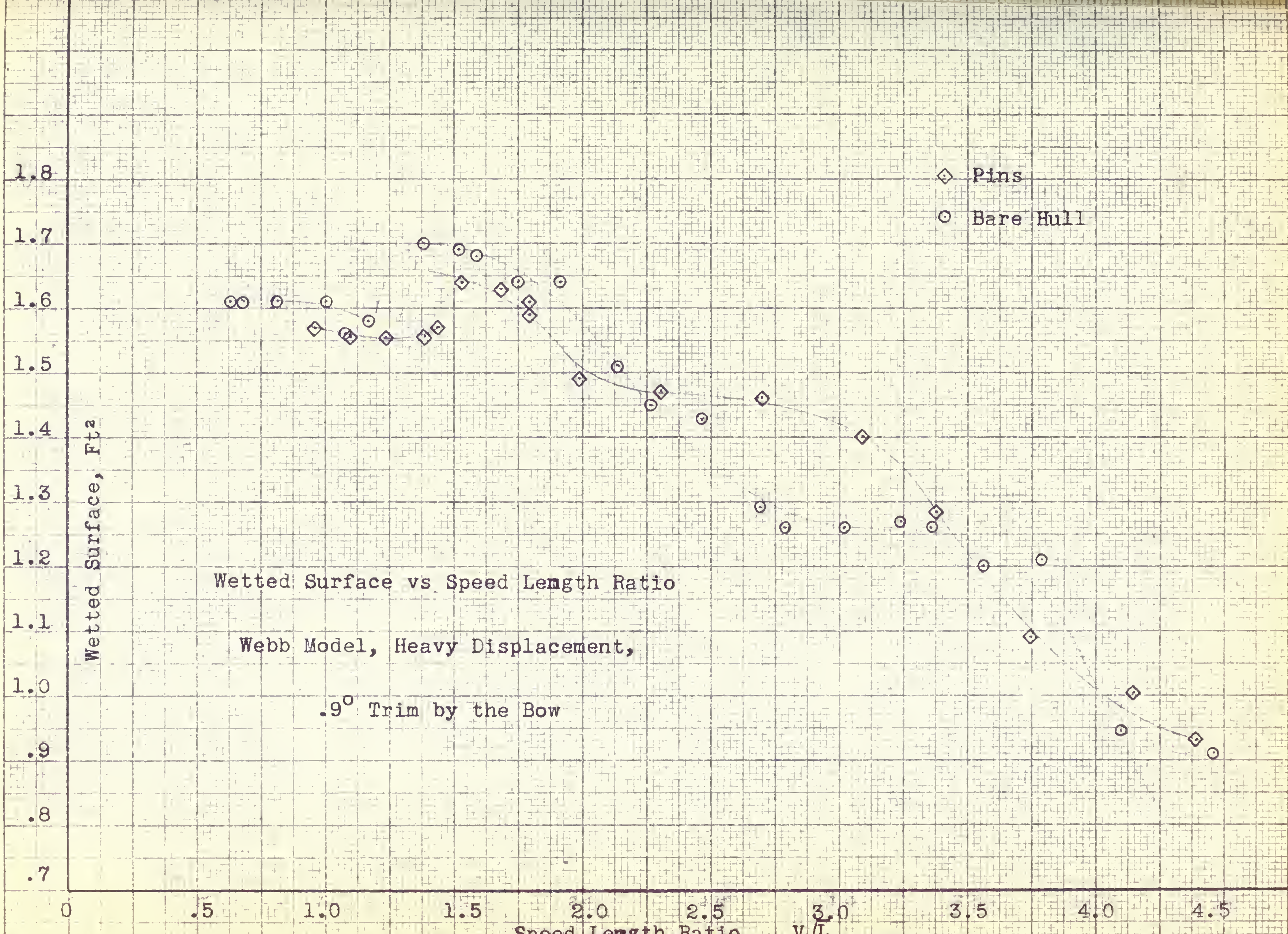

Pins
Bare Hull
Wetted Surface vs Speed Length Ratio
Webb Model, Heavy Displacement,
.9° Trim by the Bow
Wetted Surface, Ft²
Speed Length Ratio V/√L
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5

FIGURE 17

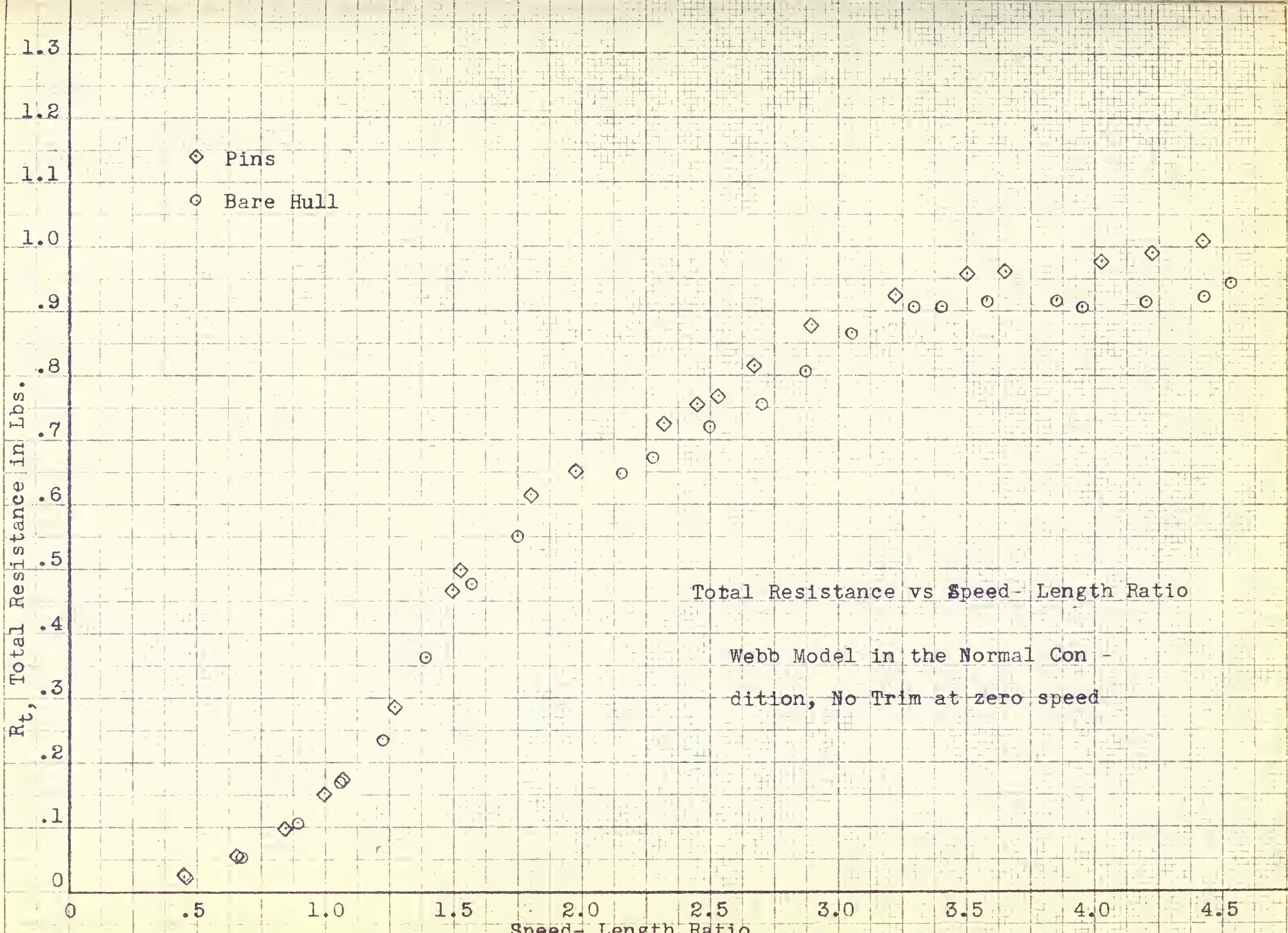

1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
R_t, Total Resistance in Lbs.
Pins
Bare Hull
Total Resistance vs Speed- Length Ratio
Webb Model in the Normal Con -
dition, No Trim at zero speed
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Speed- Length Ratio

FIGURE 18

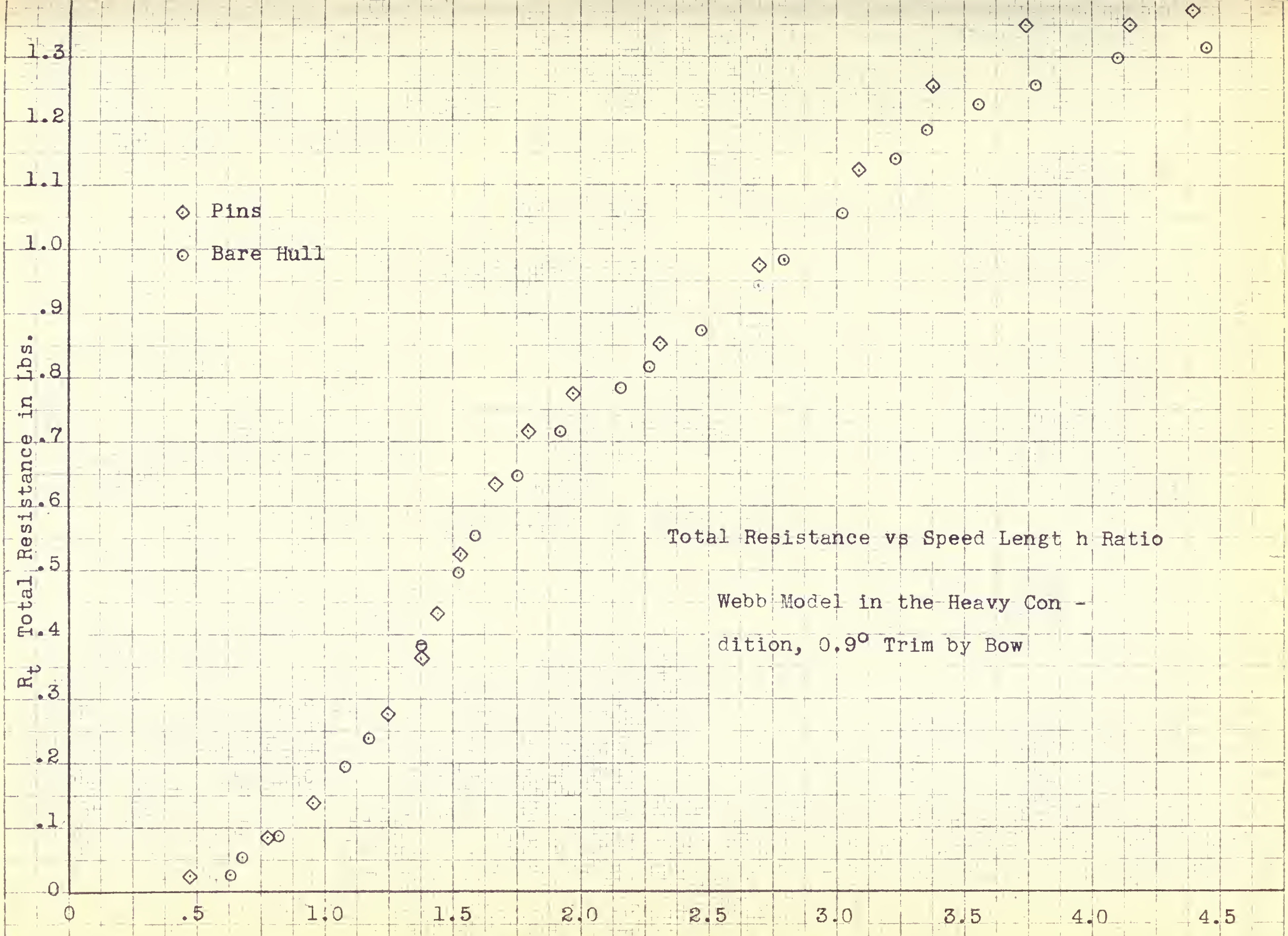

Pins
Bare Hull
Total Resistance vs Speed Lengt h Ratio
Webb Model in the Heavy Con -
dition, 0.9° Trim by Bow
R_t Total Resistance in Lbs.
Speed- Length Ratio
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5

FIGURE 19

DISCUSSION

With the data generously made available by the David Taylor Model Basin plus the data from the small model tests at Webb, an attempt was made to obtain a satisfactory viscous slope for expansion from model to full scale. The method proposed by Hughes in reference 5 was used since it takes into account form factors and, also, since most recent data on geometric series have been published in this form. Hughes proposes that resistance be divided into two parts as follows:

1. Viscous resistance includes two dimensional plate friction and form resistance which is the excess over plate resistance experienced by the hull if deeply submerged as part of a double model.
2. Wave resistance, being the excess of the total resistance of the surface model above that of the deeply submerged model when part of a double model.

These resistances cannot be separately measured on a surface model.

In order to calculate the total resistance coefficient, C_t, and Reynolds Number, the values of mean length and wetted surface at even speed-length ratios were needed. These vary with speed on planing hulls. The waterplane or solid water intersection with the chine and the forward intersection of the keel were used to determine the lengths on the chine and the keel which were averaged to obtain L_m, the mean wetted length. The total wetted surface consists of the bottom wetted surface

and the side wetted surface. The bottom wetted surface was determined from the forward keel point and the waterplane intersection with the chine. The side wetted surface was determined from the wetted height at the transom and the secondary point on the chine. Plots obtained at the David Taylor Model Basin were used to determine these wetted surfaces. This secondary point is a point aft of the solid water intersection where side wetting begins. The side wetted surface diminishes to zero at the pure planing speed (speed-length of 3.5). These values of S_t and L_m for the actual test points were plotted vs. speed-length and their values at even speed-lengths recorded and used in the calculation of C_t and R_e. It must be noted here that the length used to calculate speed-length for both conditions was the still water length in the normal condition with no trim.

The values of C_t were plotted against Log $_{10}$ Reynolds No. for all models in both the normal and heavy conditions for speed-lengths from 1.75 to 4.5. These plots are included as Figures 20-28. It is immediately apparent that a line through points of corresponding speeds has a much steeper slope than any existing friction line now used to expand from model to the full scale hull. The resistance of the largest model, No. 4023, plots high compared to the other models and appears to include some restricted channel effects. Model 4022 was chosen as the largest model which gave test results consistent with the other models.

In order to get the highest possible slope, the C_t of the

Webb model and the C_t of Model 4022 were used. To get the lowest possible slope, the C_t of the bare hull Webb model and model 4022 were used. The correct slope probably lies between these values. The slopes or form factors determined at certain speed-lengths for the two conditions are listed in Table III and plotted in Figures 29 and 30 as a form factor function. Above a speed-length of 1.5, the average bare hull form factor was approximately 2.3 while the average form factor with the Webb Model stimulated was 2.7. These form factors were taken from Figure 31. A mean value of 2.5 may give reasonable results. It is significant that this average of 2.5 is the same for both conditions of trim and displacement. This slope is unusually steep when compared to the Schoenherr line or to the newer International Towing Tank Conference line of 1957. Such a steep slope could result in a large variation in EHP predictions for the full scale vessel. In reality, this variation is modified by the increase in trim and subsequent decrease in wetted surface as model size decreases.

Another factor to be noted is the fact that by using the average form factor of 2.5 for expansion, a negative C_r could result for some of the higher speeds. The expansion to full scale can still be made using this negative C_r value.

At speed-lengths below 1.5, it is more difficult to arrive at an average slope since much laminar flow is present. Using the Webb Model stimulated and Model 4022, the average form factor is much closer to 1.0. These values for the normal condition are shown in Figure 32. Only the normal condition was analyzed

since insufficient low speed data for the models tested at the David Taylor Model Basin in the heavy condition were available. At a speed-length of 1.5, there is discontinuity in the curves of L_m and S_t. This discontinuity came slightly before a speed-length of 1.5 in the heavy condition because the length used in the speed-length value is for the normal condition.

Blockage factors and tank critical speeds were calculated and are given in Table IV. The values given for the Webb tank are for the lower tank level used during the test. Based upon the results of tests in the DTMB High Speed Basin, the authors feel that a blockage factor of .3% begins to give erroneous results.

Smaller models, because of their lower Reynolds number, have a higher frictional resistance than larger models when towed at corresponding speeds. This relative increase in horizontal force, which is scaled to give a vertical force, offers a possible explanation for the increase in trim as model size decreased. The Webb model was towed using both vertical and horizontal weights. The vertical component was calculated by multiplying the horizontal force times the tangent of the towing angle (change of trim plus shaft angle). Since the horizontal force is relatively greater for the smaller model, the vertical force must also be larger. This relative increase in vertical weight definitely causes some of the increase in trim and could account for all of it. No tests were conducted to verify this scaled vertical effect because time was not available. The DTMB models were towed with an automatic towing arm which, once set, maintained the proper towing angle. The

vertical force was not measured or recorded. A comparison of the trims of the Webb model, Model 4020, and Model 4022 is shown in Figures 33 and 34.

To illustrate the above statement, the values of resistance, trim, and vertical force for the Webb model and Model 4022 at a speed-length of 2.5 are compared below.

MODEL	LINEAR RATIO	SPEED LENGTH RATIO	R	TRIM	TRIM plus SHAFT ANGLE	VERT. FORCE
4022	6.75	2.5	37.40	2.97°	14.87	9.9
Webb	27.0	2.5	0.77	3.50°	15.40	0.212

$$\frac{\text{Vertical Force of 4022}}{(\text{Linear Ratio})^3} = \frac{9.9\#}{64} = .155\#$$

The addition of .05# in the still condition caused an increase in trim of 0.133° and should cause more at planing speeds. This trim effect was probably accentuated in this series by the high shaft angle involved. Towing all models with only a horizontal component might be one means of achieving a true geometric series.

To check on the effect of decreasing wetted surface with size of model, the wetted surfaces of model 4022 were scaled down and used to calculate the C_t of several speed-lengths for the Webb model. The form factors decreased, but were still fairly high. These values are given in the following table.

	SCALED WETTED SURFACE		ACTUAL WETTED SURFACE	
SPEED LENGTH RATIO	BARE HULL SLOPE	STIM. SLOPE	BARE HULL SLOPE	STIM. SLOPE
3.25	2.2	2.6	3.1	3.0
3.50	1.9	2.5	3.0	3.1
4.00	1.2	1.7	2.3	2.7

The authors believe that a retest of the small model with the scaled down vertical component of model 4022 at each speed should show a significant difference in trim and wetted surface. Also the vertical weight could be varied at each speed and a plot constructed showing the weight needed to change trim by $.5^\circ$ or 1° at each speed.

With turbulence stimulation, the small Webb model showed an increase of 4-7% in total resistance. These tests showed that laminar flow existed in the bare hull tests at planing speeds. Because of the presence of laminar flow on the small model at all speeds and on at least three of the DTMB models at low speeds, it is possible that laminar flow exists in some of the DTMB models at higher speeds.

During the turbulence stimulation tests, no noticeable differences were detected in the change of trim but a plot of the final results with stimulation showed a definite increase in mean length and wetted surface between speed-lengths of 2.5 and 3.5. The trim of the stimulated model decreased slightly in the same range of speed-length ratios. The heavy condition tests showed a larger increase in wetted surface and mean length than the bare hull test at these speed-length ratios.

If a full scale bare hull data had been available, an attempt would have been made to expand from model to full scale and thereby determine a suitable roughness allowance for use with this expansion method.

DATA CALCULATIONS
PRNC-GEN-126

TABLE III

Hughes Form Factors

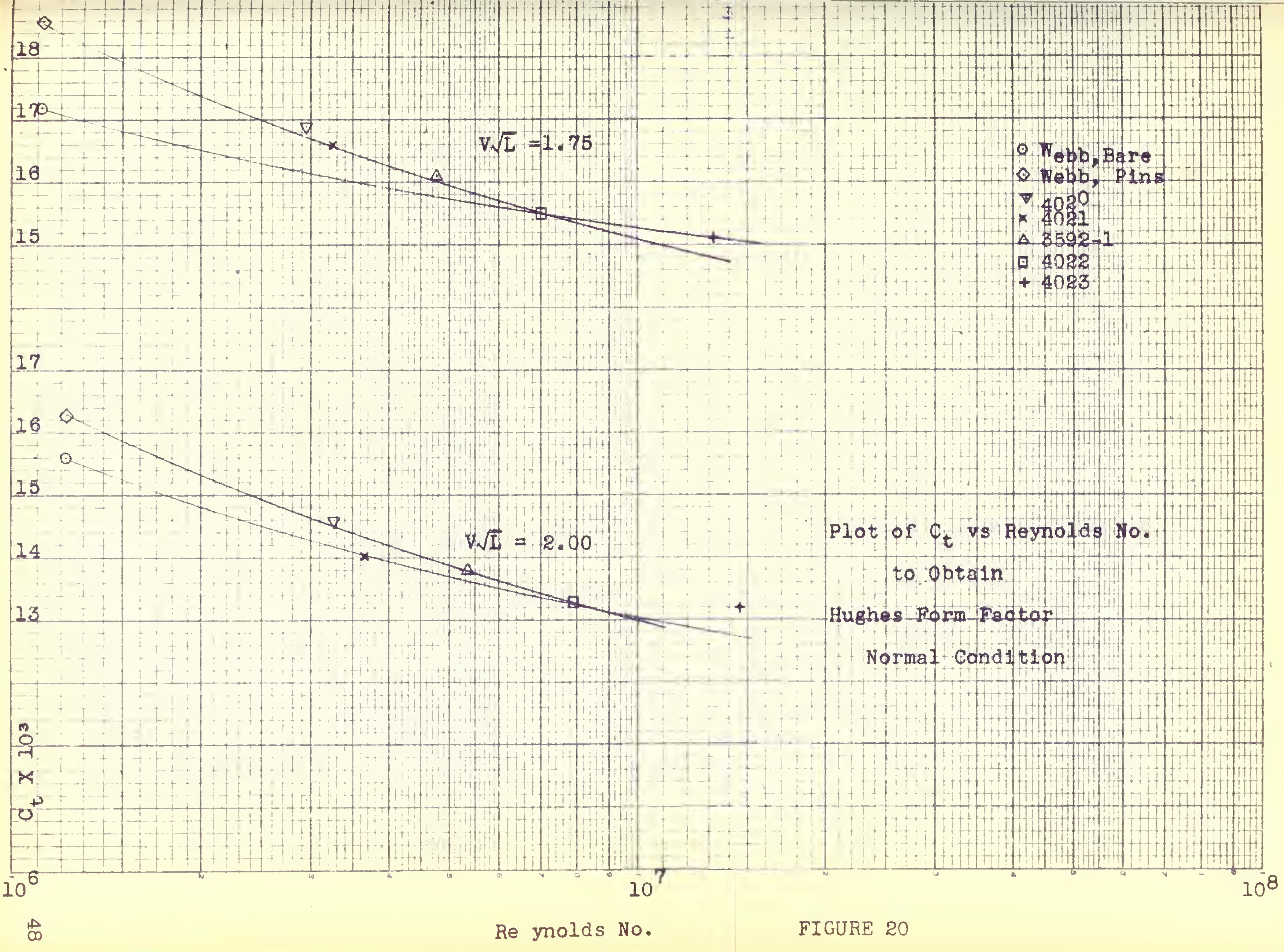
Speed - Length Ratio		Normal Displ. Webb Bare	Normal Displ. Webb Stim.	Heavy Displ. Webb Bare	Heavy Displ Webb Stim.
1.75		1.40	2.50	1.10	2.40
2.00		2.00	2.60	1.30	2.60
2.25		2.00	2.50	2.25	2.60
2.50		2.00	2.50	2.90	2.50
2.75		1.95	2.50	3.10	2.40
3.00		2.25	2.65	3.00	2.40
3.25		3.10	3.00	2.80	2.10
3.50		3.00	3.10	2.50	3.10
4.00		2.30	2.70	2.70	3.10
4.50		1.70	2.90	2.70	2.90
	Totals	21.70	26.95	24.35	26.10
	Average	2.17	2.695	2.435	2.61
	Overall	Average -	2.477		

NAVY-DPPO PRNC, WASH., D.C.

TABLE IV

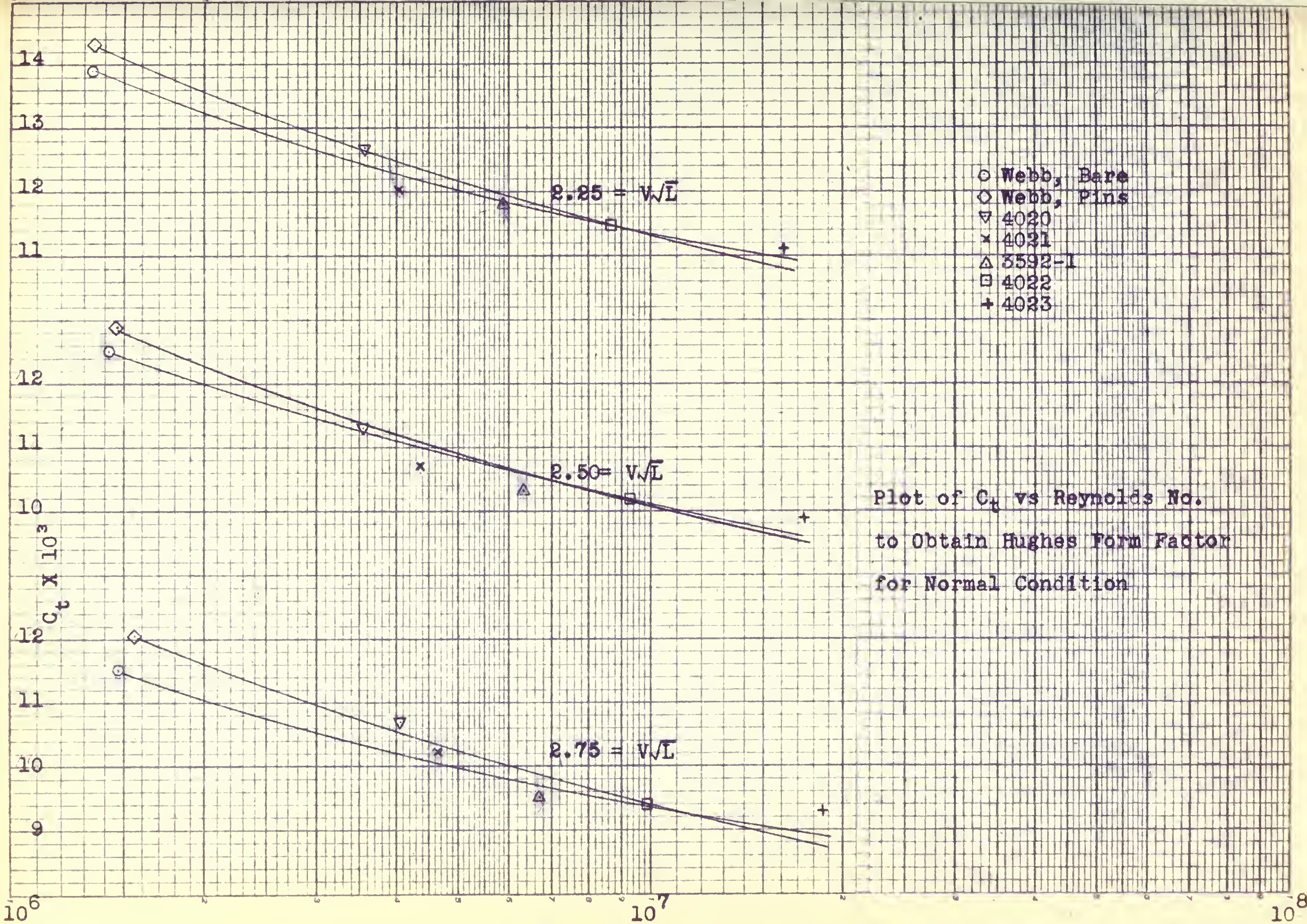
BLOCKAGE FACTORS AND CRITICAL SPEEDS

Model	Linear Ratio	Area of Largest Section Ft^2	Area of Tank Ft^2	Blockage Factors	
Webb	27.0	.0388	47.6	.0815%	Area of Webb Tank at Normal level is 50 ft^2.
4020	13.5	.1552	1122.0	.014%	
4021	11.25	.2235	1122.0	.0199%	
3592-1	9.0	.3493	1122.0	.031%	
4022	6.75	.6208	1122.0	.055%	
4023	4.5	1.3968	1122.0	.124%	
Values for DTMB High Speed Basin					
3592-1	9.0	.3493	210	.166%	
4022	6.75	.6208	210	.296%	Results of this test showed restricted channel effects.
4023	4.5	1.3968	210	.665%	Results of this test showed restricted channel effects.



18
17
16
15
17
16
15
14
13
C_t X 10^3
$V\sqrt{L}$ =1.75
$V\sqrt{L}$ = 2.00
⊙ Webb, Bare
◇ Webb, Pins
▽ 4020
× 4021
△ 3592-1
□ 4022
+ 4023
Plot of C_t vs Reynolds No.
to Obtain
Hughes Form Factor
Normal Condition
10^6
10^7
10^8
Re ynolds No.

FIGURE 20



Reynolds No.

FIGURE 21

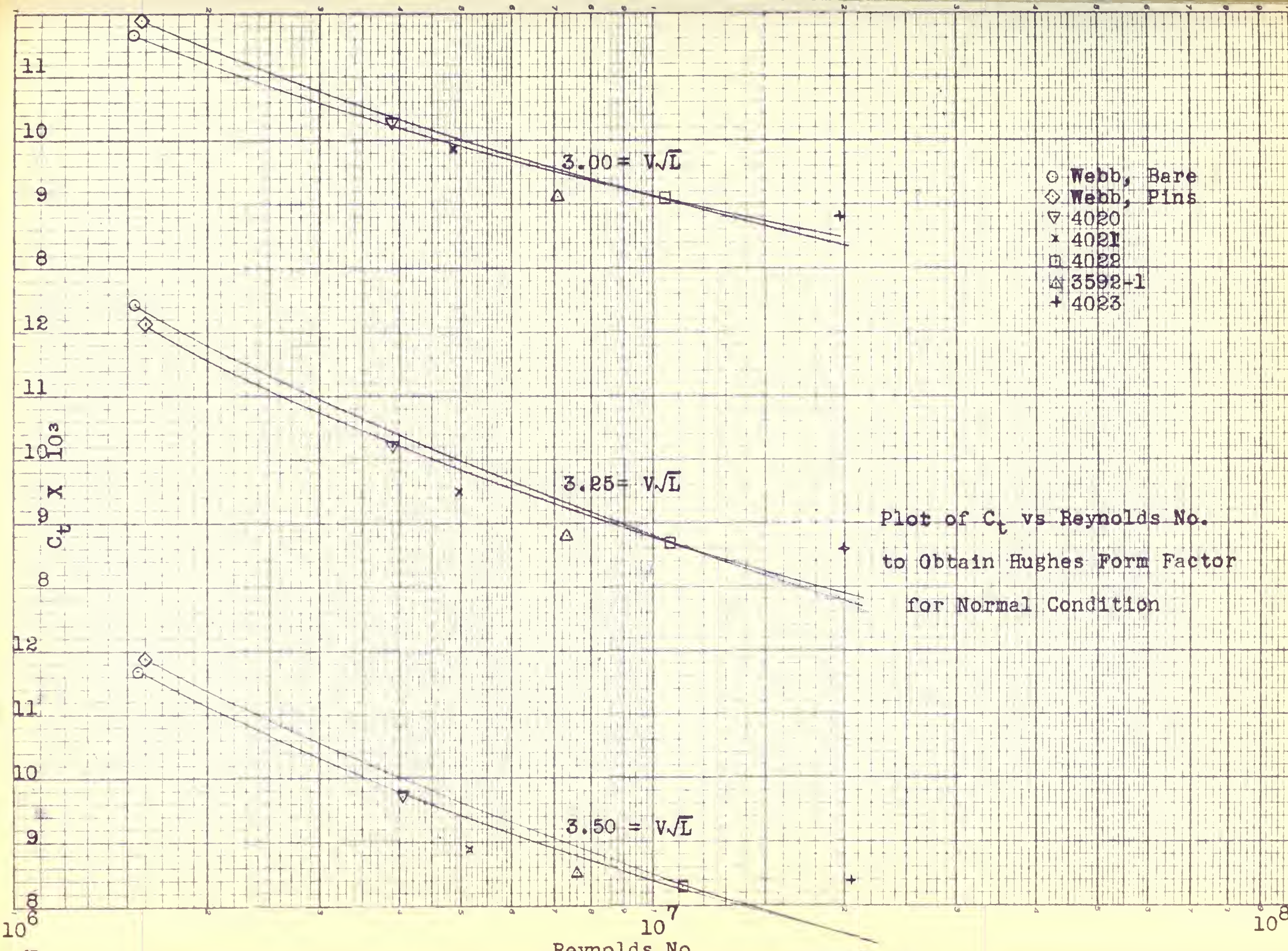
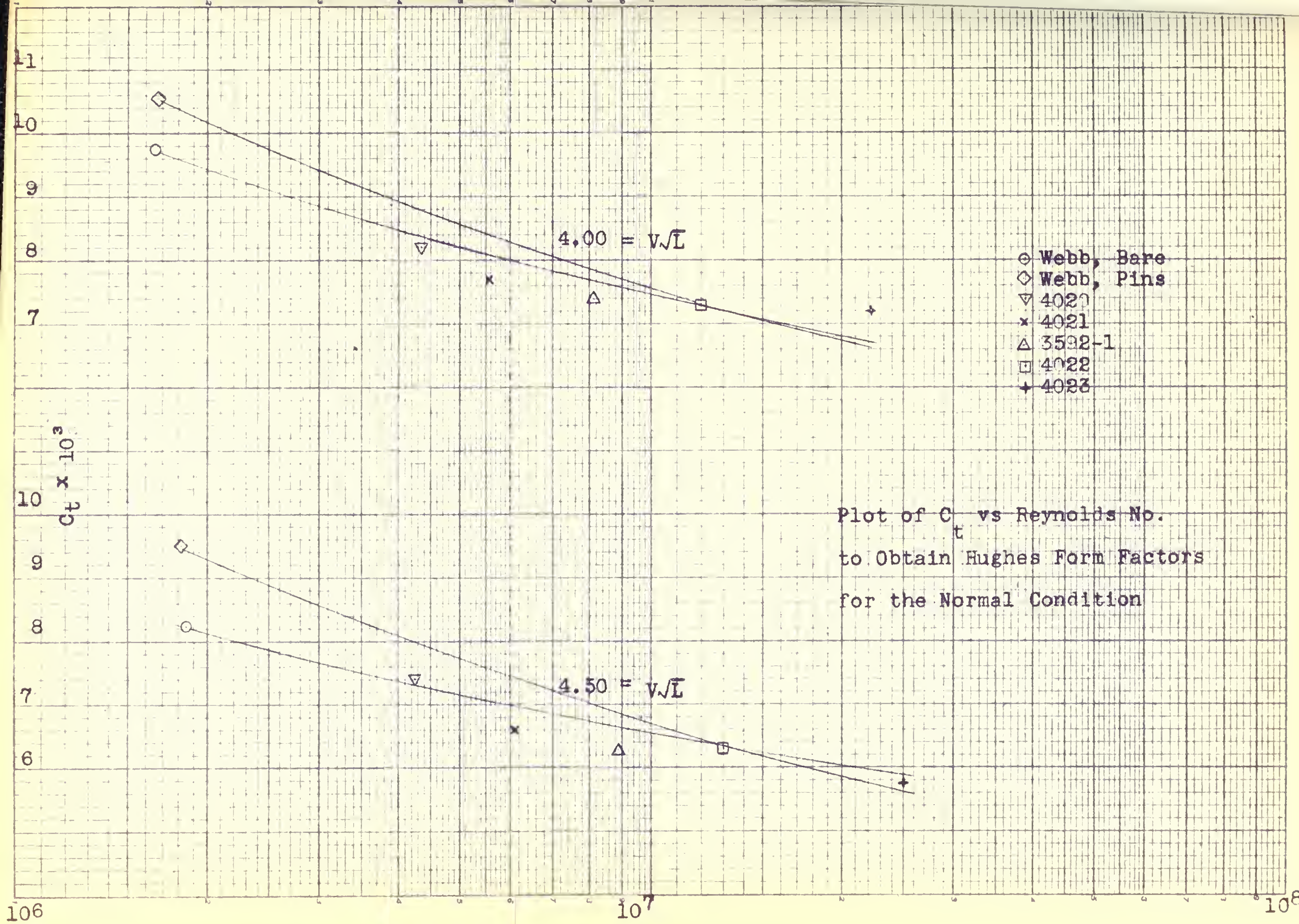
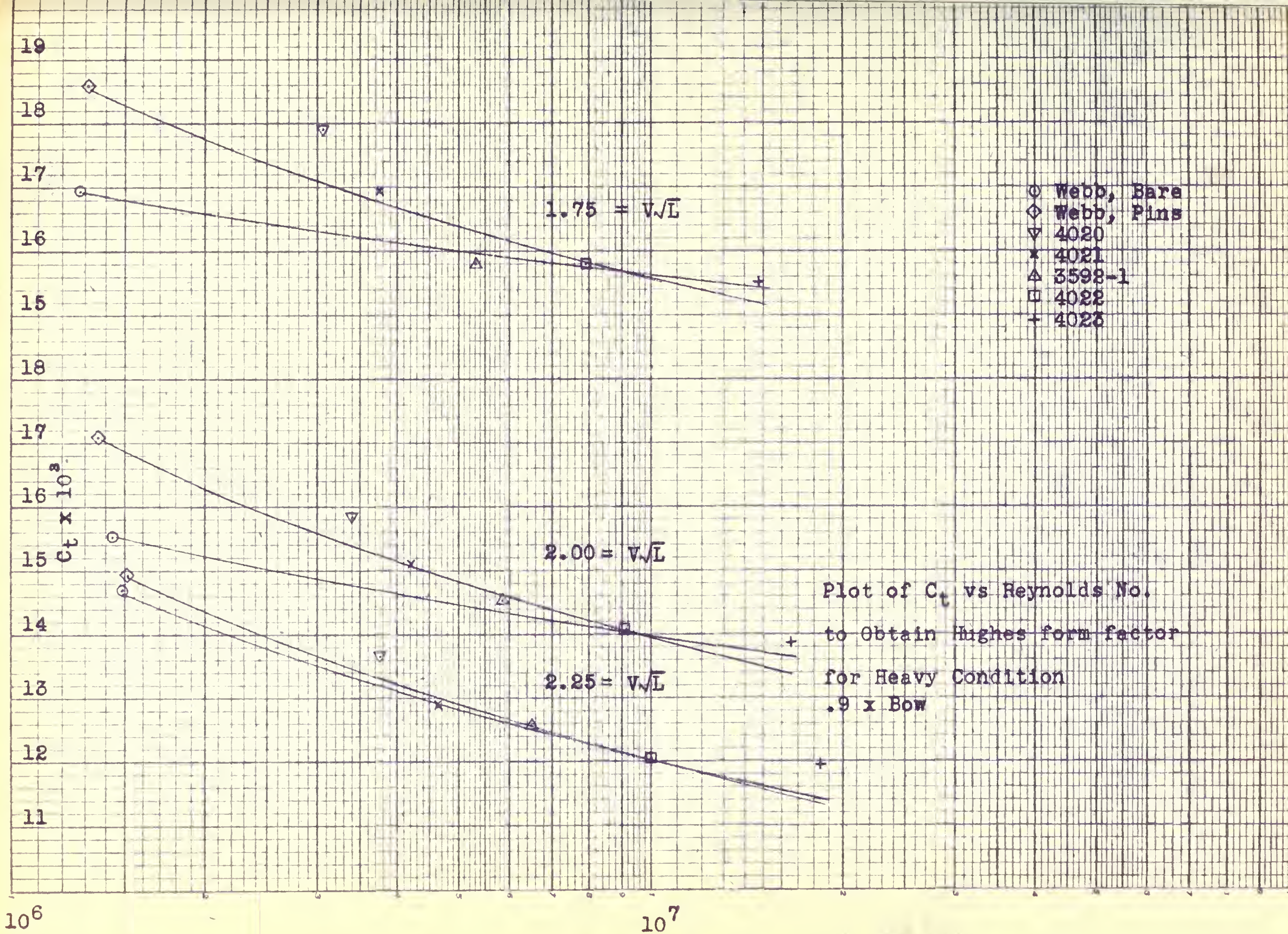

Webb, Bare
Webb, Pins
4020
4021
4022
3592-1
4023
3.00 = V√L
3.25 = V√L
3.50 = V√L
Plot of C_t vs Reynolds No.
to Obtain Hughes Form Factor
for Normal Condition
$C_t \times 10^3$
Reynolds No.
10^6
10^7
10^8
11
10
9
8
12
11
10
9
8
12
11
10
9
8

FIGURE 22



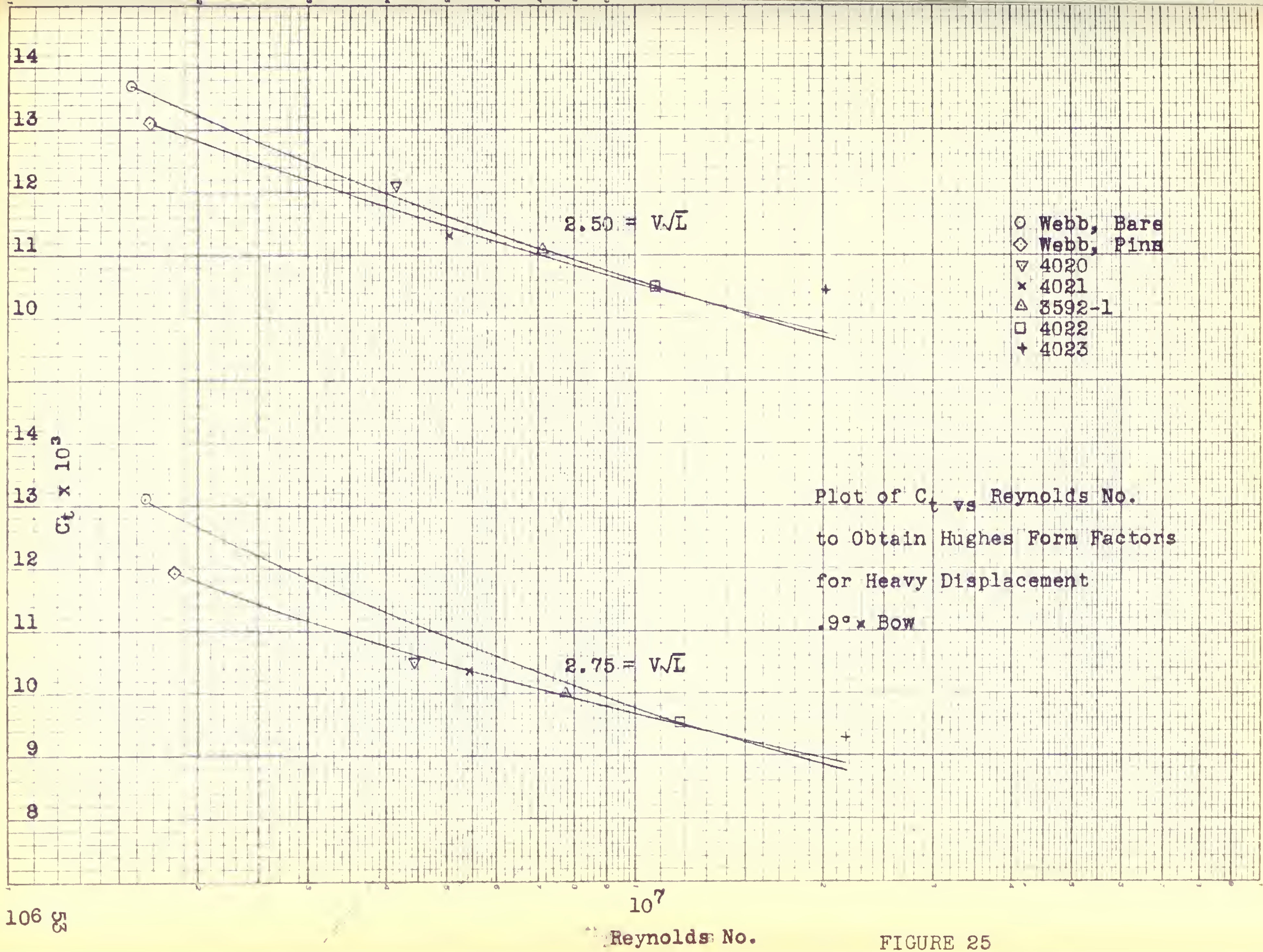
$C_t \times 10^3$
4.00 = $V/\sqrt{L}$
4.50 = $V/\sqrt{L}$
Webb, Bare
Webb, Pins
4020
4021
3592-1
4022
4023
Plot of C_t vs Reynolds No.
to Obtain Hughes Form Factors
for the Normal Condition
10^6
10^7
10^8
Reynolds No.

FIGURE 23



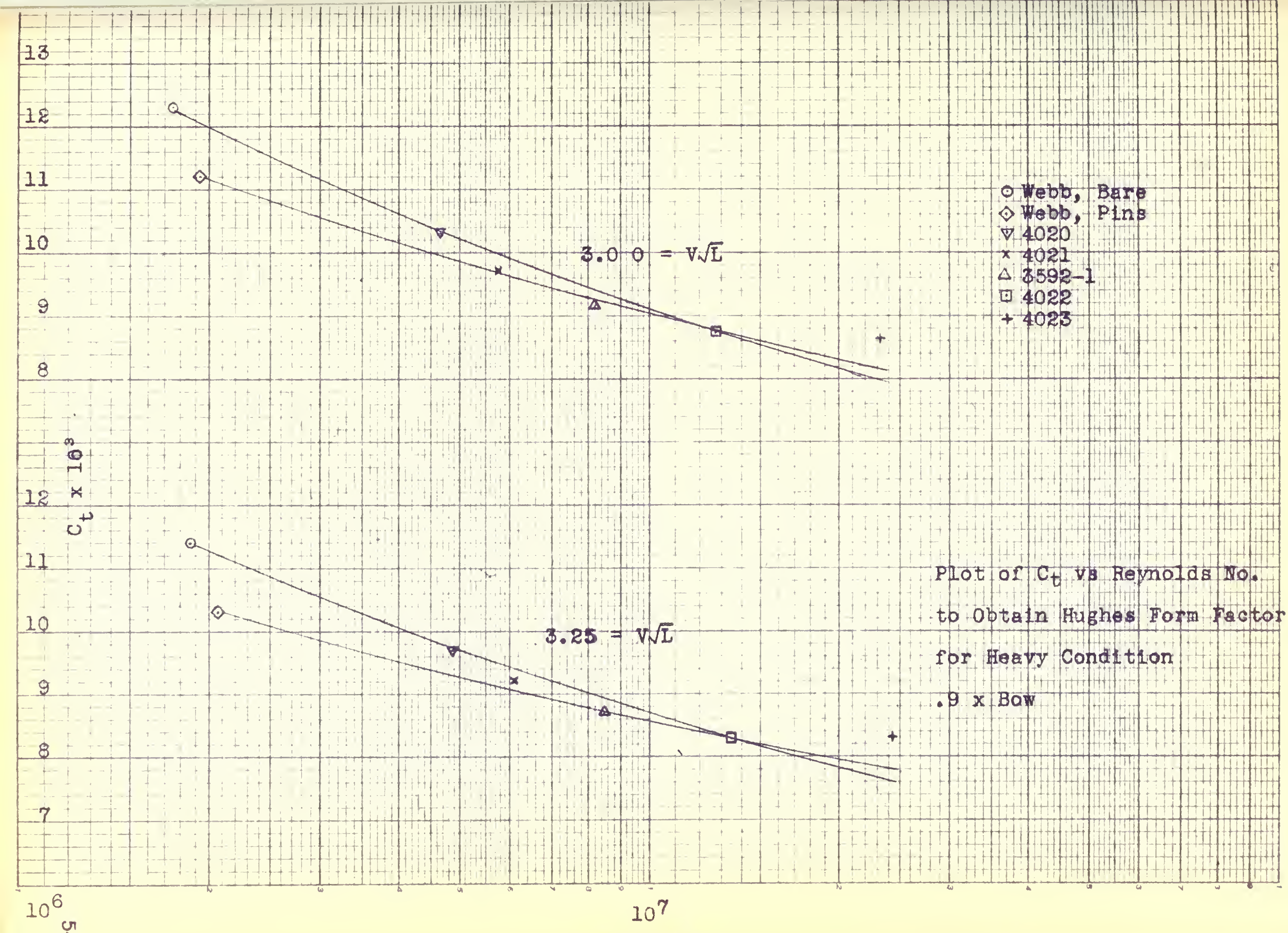
Reynolds No.

FIGURE 24



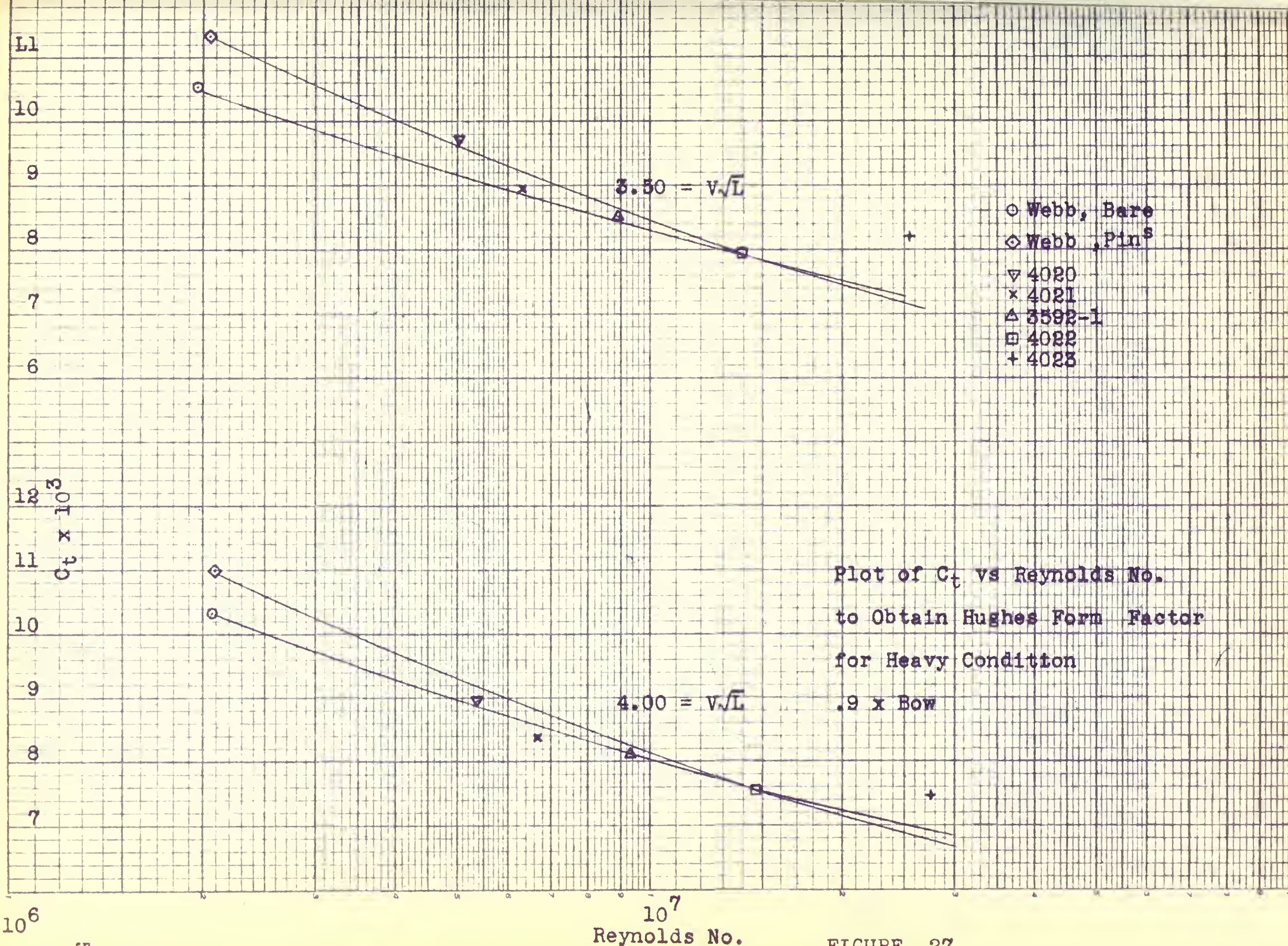
14
13
12
11
10
14
13
12
11
10
9
8
$C_t \times 10^3$
2.50 = V√L
2.75 = V√L
○ Webb, Bare
◇ Webb, Pins
▽ 4020
× 4021
△ 3592-1
□ 4022
+ 4023
Plot of C_t vs Reynolds No.
to Obtain Hughes Form Factors
for Heavy Displacement
.9° x Bow
106
10^7
Reynolds No.

FIGURE 25



13
12
11
10
9
8
12
11
10
9
8
7
$C_t \times 10^3$
⊙ Webb, Bare
◇ Webb, Pins
▽ 4020
× 4021
△ 3592-1
⊡ 4022
+ 4023
3.0 0 = V√L
3.25 = V√L
Plot of C_t vs Reynolds No.
to Obtain Hughes Form Factor
for Heavy Condition
.9 x Bow
10^6
10^7
Reynolds No.

FIGURE 26



11
10
9
8
7
6
12
11
10
9
8
7
$C_t \times 10^3$
$3.50 = V\sqrt{L}$
$4.00 = V\sqrt{L}$
Webb, Bare
Webb ,Pins
4020
4021
3592-1
4022
4023
Plot of C_t vs Reynolds No.
to Obtain Hughes Form Factor
for Heavy Condition
.9 x Bow
10^6
10^7
Reynolds No.

FIGURE 27

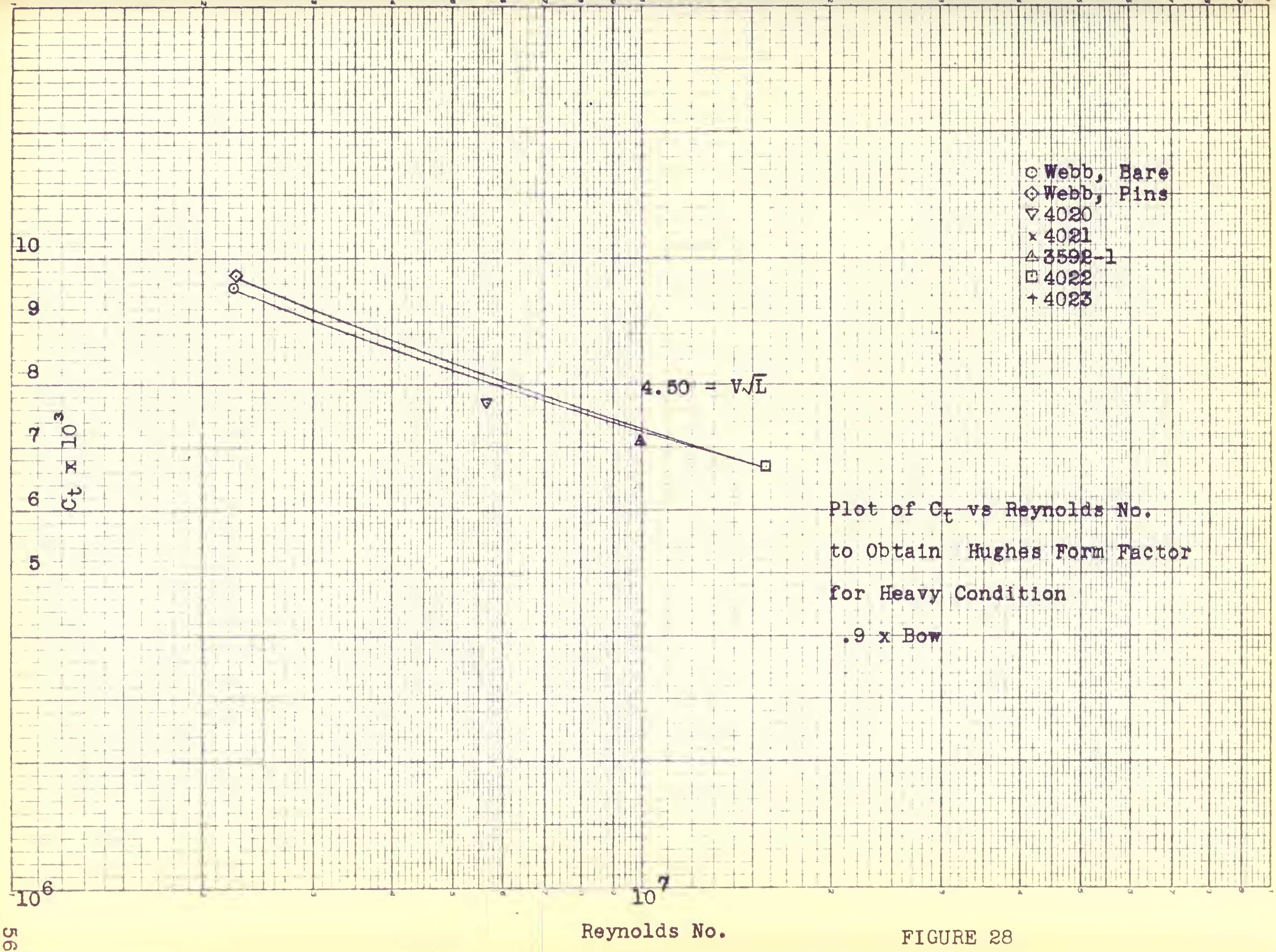

Webb, Bare
Webb, Pins
4020
4021
3592-1
4022
4023
10
9
8
7
6
5
$C_t \times 10^3$
$4.50 = V\sqrt{L}$
Plot of C_t vs Reynolds No.
to Obtain Hughes Form Factor
for Heavy Condition
.9 x Bow
10^6
10^7
Reynolds No.

FIGURE 28

Plot of Hughes Form Factors

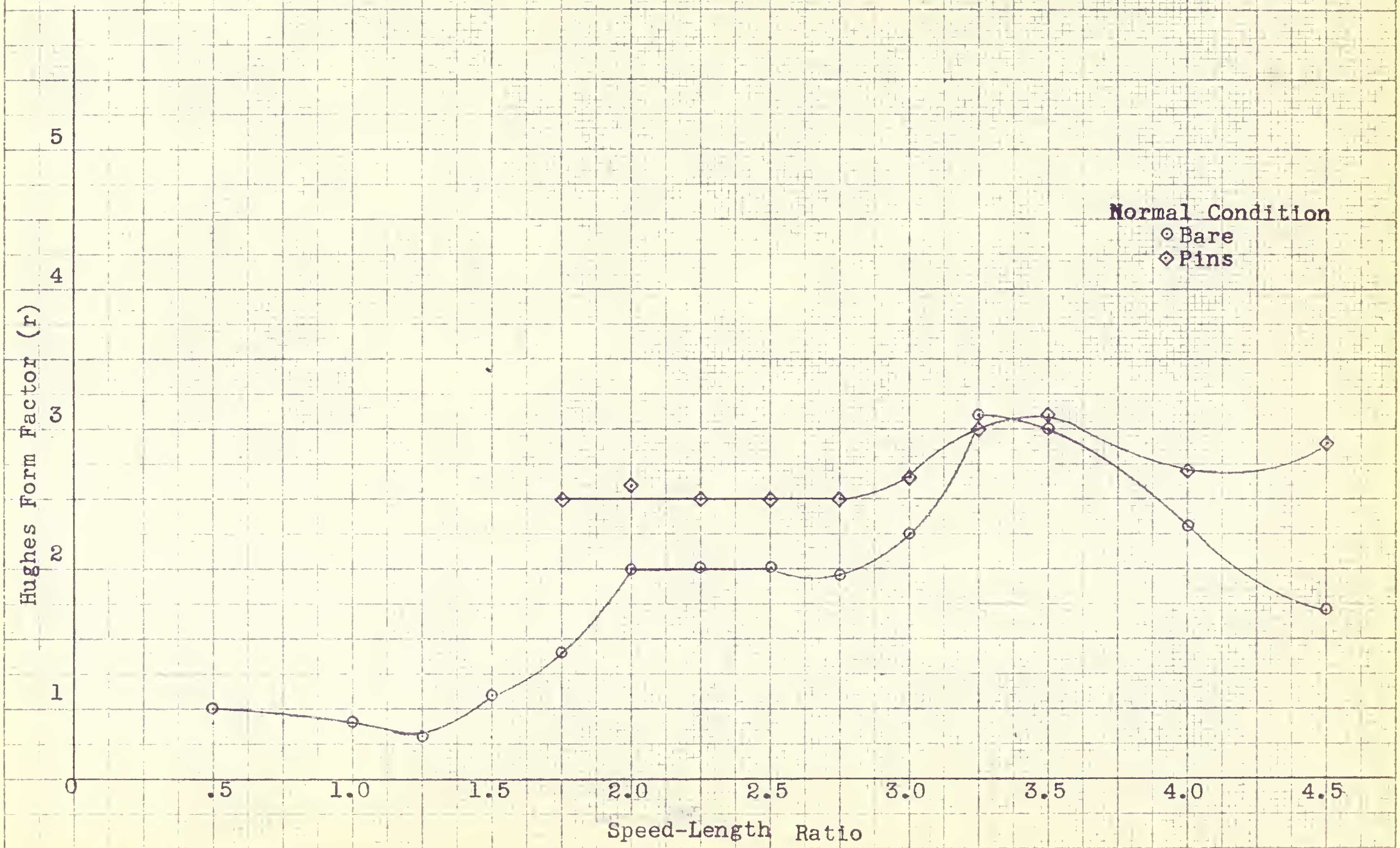


Figure 29

Plot of Hughes Form Factors

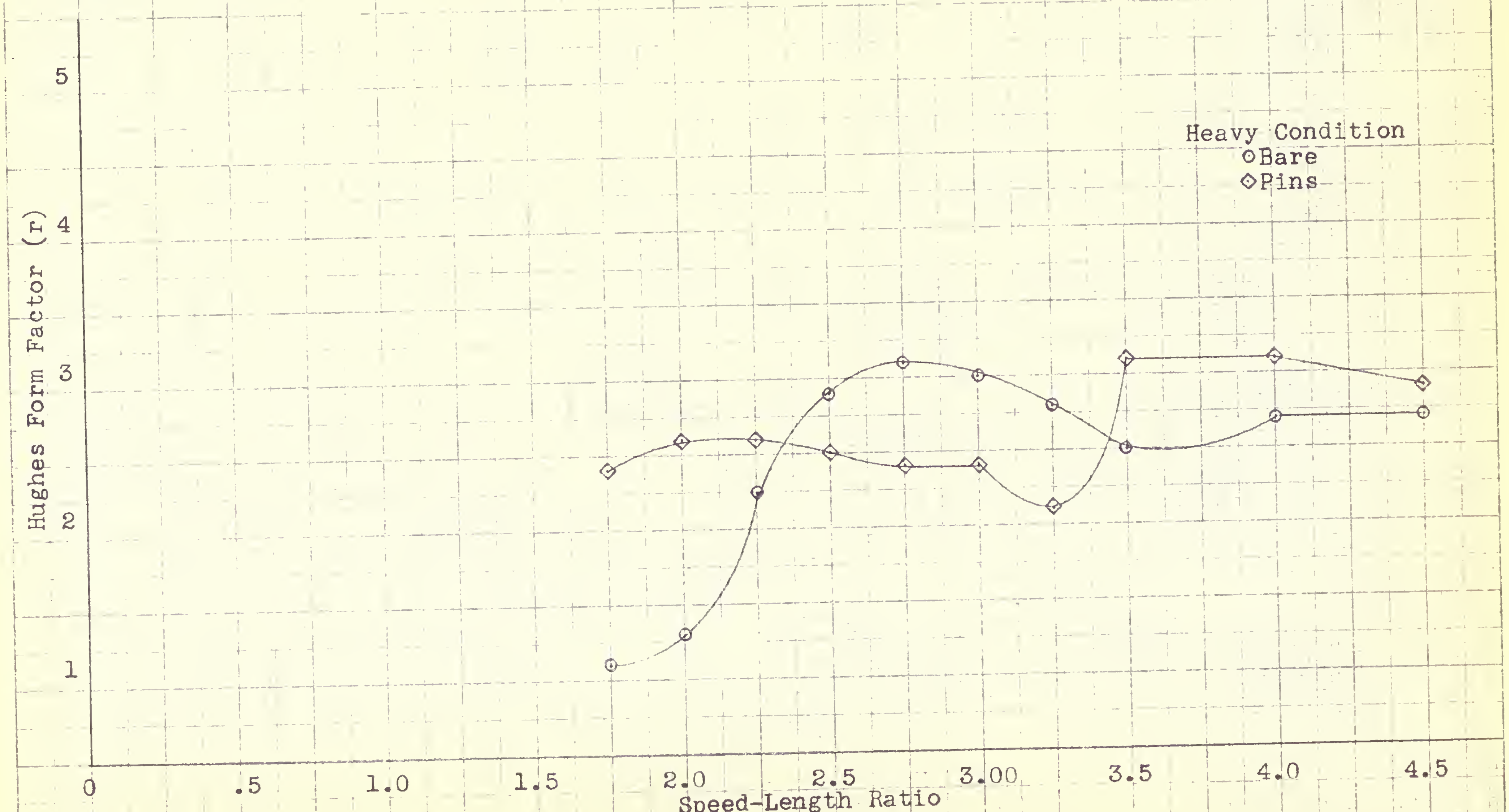
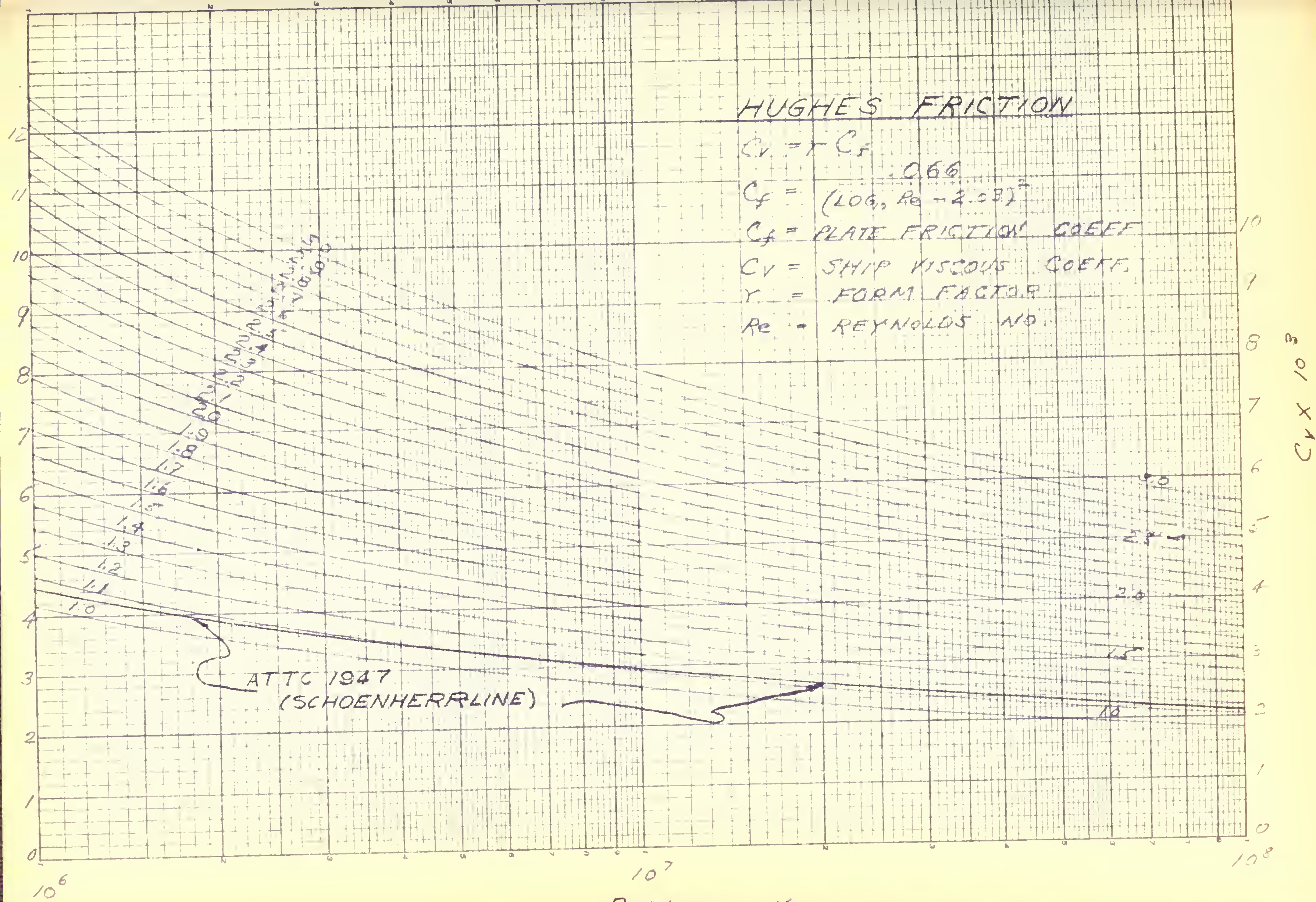
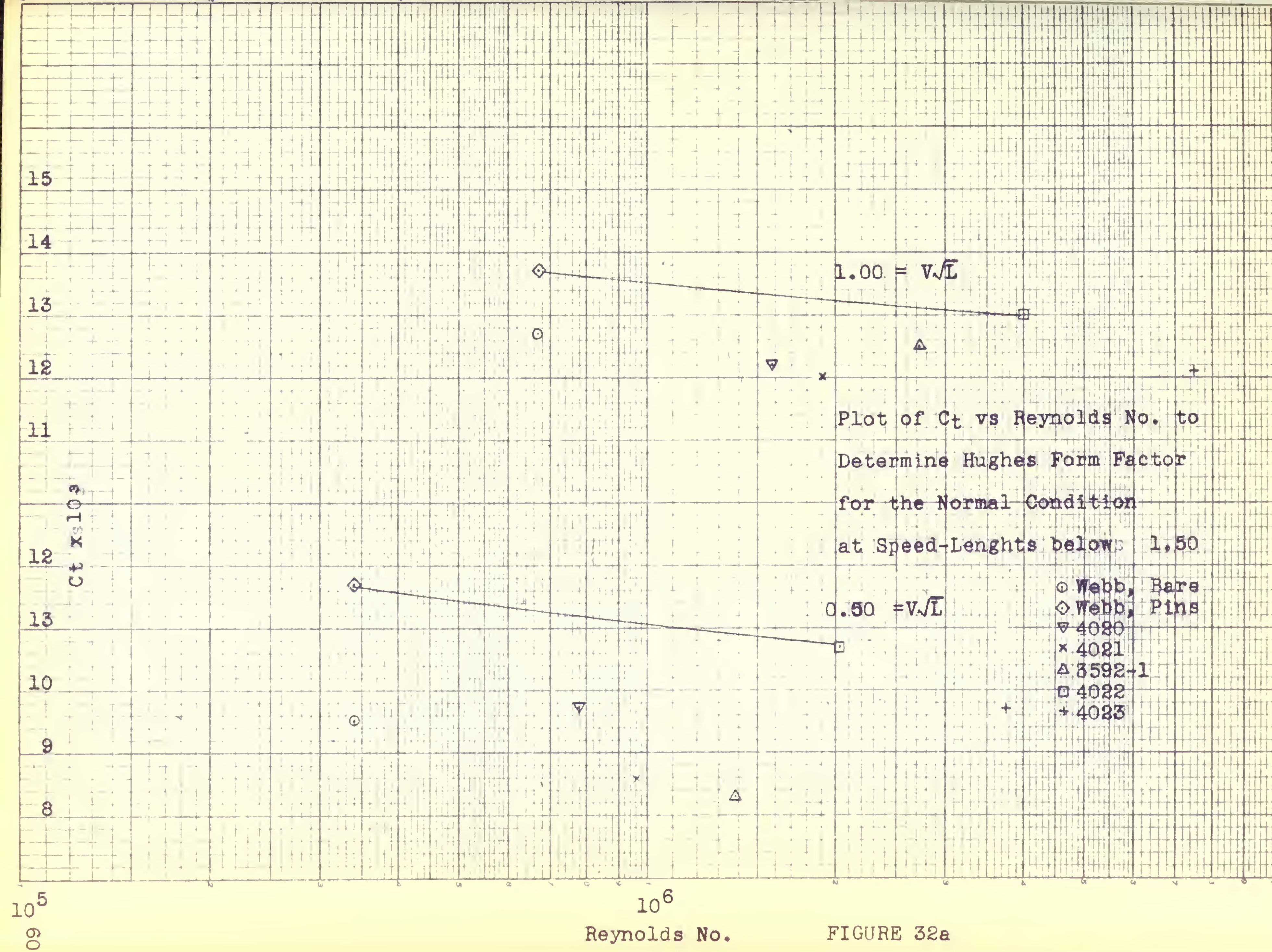


Figure 30



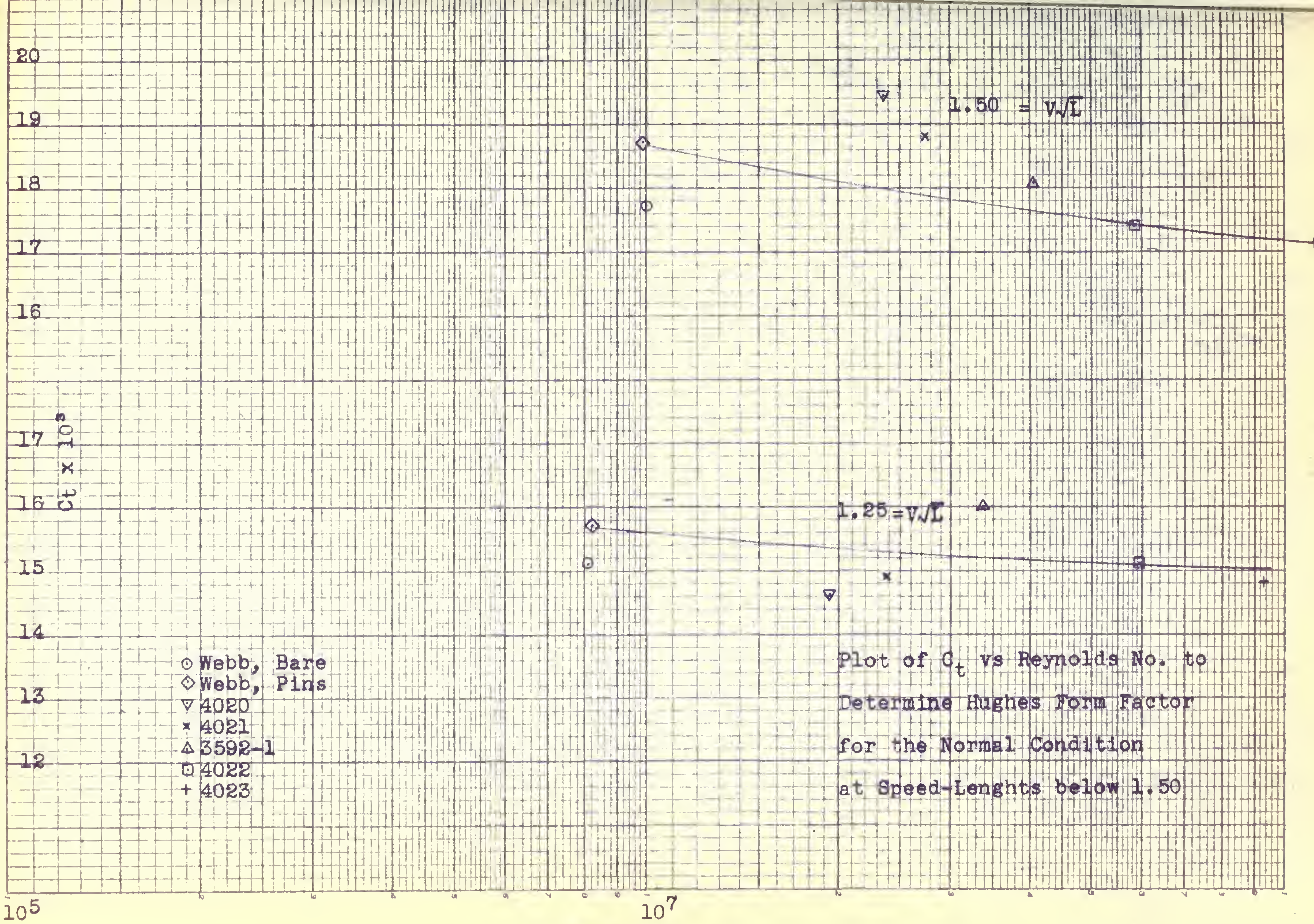
HUGHES FRICTION
$C_V = r\,C_f$
$C_f = \dfrac{.066}{(\log_{10} Re - 2.03)^2}$
C_f = PLATE FRICTION COEFF
C_V = SHIP VISCOUS COEFF
r = FORM FACTOR
Re = REYNOLDS NO
ATTC 1947
(SCHOENHERRLINE)
$C_V \times 10^3$
REYNOLDS NO.

FIGURE 31



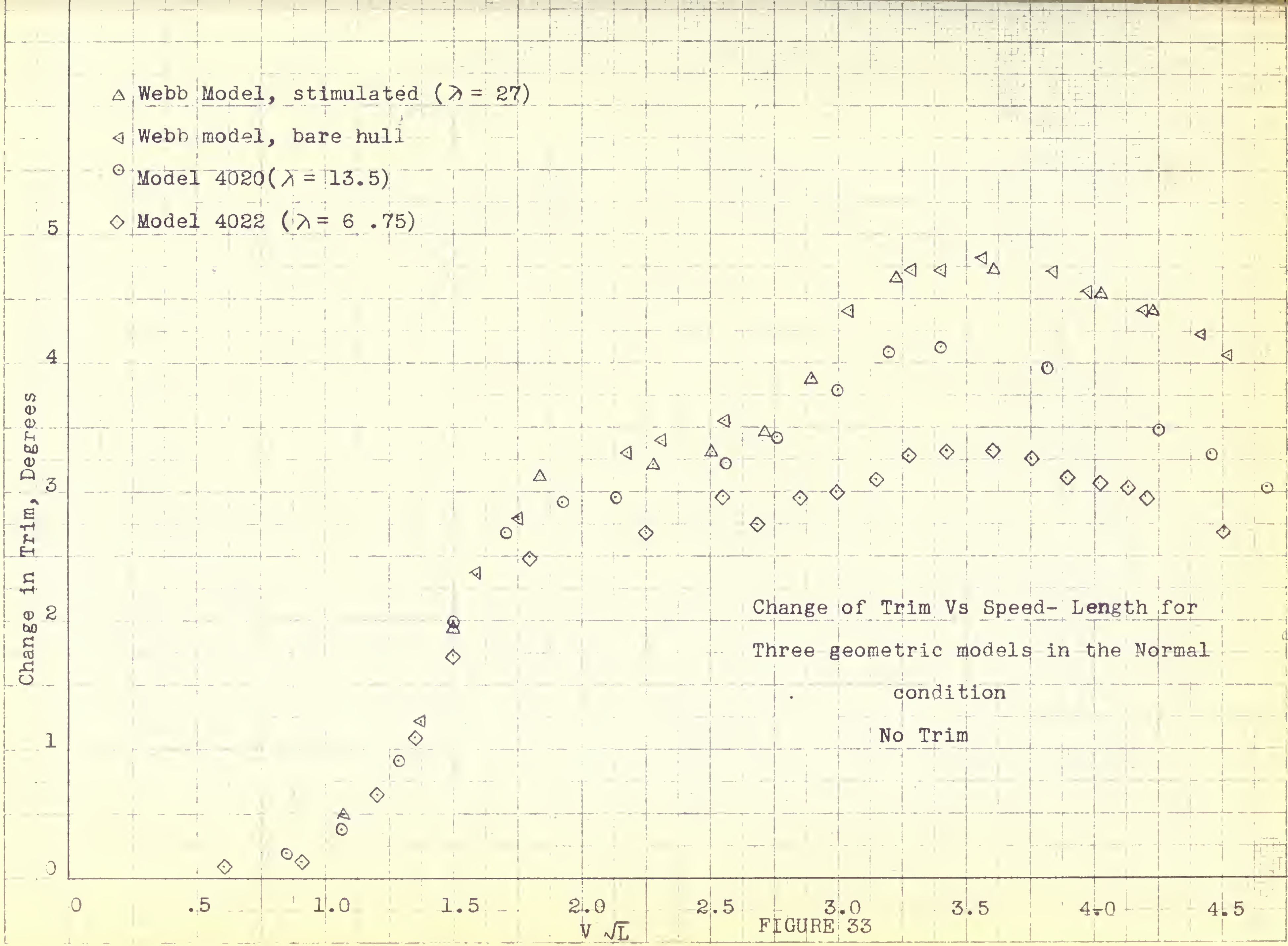
15
14
13
12
11
12
13
10
9
8
Ct x 10³
10^5
10^6
1.00 = V/√L
0.50 =V/√L
Plot of C_t vs Reynolds No. to
Determine Hughes Form Factor
for the Normal Condition
at Speed-Lenghts below 1.50
⊙ Webb, Bare
◇ Webb, Pins
▽ 4080
× 4021
△ 3592-1
□ 4022
+ 4023
Reynolds No.

FIGURE 32a



20
19
18
17
16
17
16
15
14
13
12
$C_t \times 10^3$
1.50 = V/√L
1.25 = V/√L
⊙ Webb, Bare
◇ Webb, Pins
▽ 4020
× 4021
△ 3592-1
⊡ 4022
+ 4023
Plot of C_t vs Reynolds No. to
Determine Hughes Form Factor
for the Normal Condition
at Speed-Lenghts below 1.50
10^5
10^7
Reynolds No.

FIGURE 32b



Webb Model, stimulated (λ = 27)
Webb model, bare hull
Model 4020(λ = 13.5)
Model 4022 (λ = 6 .75)
Change in Trim, Degrees
0
1
2
3
4
5
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
V $\sqrt{L}$
Change of Trim Vs Speed- Length for
Three geometric models in the Normal
condition
No Trim

FIGURE 33

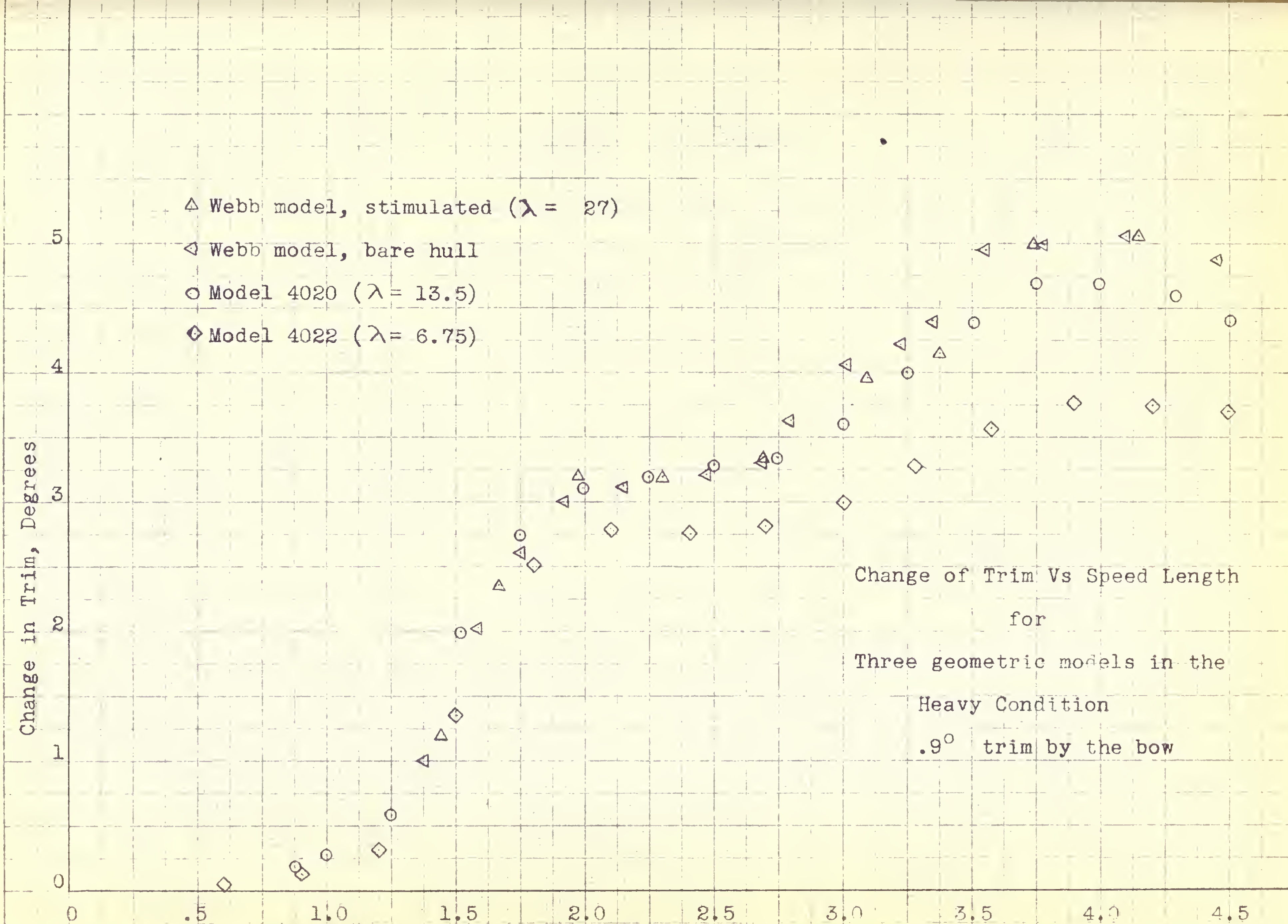

△ Webb model, stimulated (λ = 27)
◁ Webb model, bare hull
○ Model 4020 (λ = 13.5)
◇ Model 4022 (λ = 6.75)
Change of Trim Vs Speed Length
for
Three geometric models in the
Heavy Condition
.9° trim by the bow
Change in Trim, Degrees
0
1
2
3
4
5
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
V√L

FIGURE 34

CONCLUSIONS

In summarizing the results of this thesis, the authors feel the following conclusions can be made.

It is essential for consistent results that turbulence stimulation must be used in the testing of a geometric series of this type. Pins appear to give the most consistent results. The tests of the small model showed that laminar flow can be present at planing speeds. The Reynolds number of the small model varied from 3.4×10^5 to 1.8×10^6.

With turbulence stimulation, the Webb model showed an increase of total resistance of 4 to 7% over the whole speed range in both the normal and heavy displacement tests.

The plots of change in trim for the Webb model and Taylor Model Basin Models 4020 and 4022 show an increase in trim for the smaller models at the same speed-length ratio. The result of this is a reduction of both wetted surface and mean wetted length.

In the plots of slopes of total resistance coefficient, C_t, at the same speed-length ratios, these slopes are considerably higher than any values previously published. As indicated in the discussion, the mean form factor, between the speed-length ratios of 3.25 to 4.00, dropped from 2.5 to 2.1 when a scaled down value of actual wetted surface from Model 4022 was used to determine the C_t of the small model. The authors feel that if the small model were towed at the corresponding trim of Model 4022, the R_t value would have been even higher and would have resulted in a further increase of C_t and form factor.

It is felt by the authors that two reasons may account for the radical change in form factor from a mean of $1._{00}$ below a speed length ratio of 1.5 to a mean of 2.5 at a speed-length ratio greater than 1.50. The first reason may be due to comparing hull forms that are no longer either geometrically or dynamically similar at the same speed-length ratio due to the change in trim. The second reason may be the change in hull shape which will cause the form resistance (part of the total hull resistance as stated by Hughes) to become higher as the planing hull goes from a displacement to a semi-planing condition.

The authors believe that the actual slope of that portion of the hull below the water surface will remain fairly constant for various model sizes throughout the semi-planing and fully planing condition. This is due to the relative straight line portions of the after hull sections of this series. There is, however, a change in flow due to the higher trims on the smaller models.

Based on the results of this series, the authors feel that an expansion of this data by either the Schoenherr or the 1957 ITTC line will result in predicted EHP's for the full size vessel which are high. The mean form factor for an expansion, based on Hughes' friction line, is approximately 2.5 for planing hulls of this series at speed-length ratios greater than 1.50.

Additional geometric series tests must be made to determine what elements of hull shape cause variations in form factors.

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A P P E N D I C E S

SAMPLE CALCULATIONS

These calculations are for a speed-length ratio of 2.495 with the model in the normal condition.

CALCULATION OF MEAN WETTED LENGTH

$$\begin{array}{lr} \text{Total length on keel in stations} = & 9.90 \\ \text{Total length on chine in stations} = & \underline{9.806} \\ & 19.706 \end{array}$$

$$\text{Average length} = \frac{19.706}{2} = 9.853$$

The keel intersection and the waterplane intersection on the chine were averaged and subtracted from 9.853 to get the mean length in stations. This value multiplied by the station spacing in feet gave L_m, the mean length.

Example:

$WL_k = 1.8$

$WL_c = 4.4$

$$\begin{array}{r} 1.8 \\ \underline{4.4} \\ 6.2 \end{array} \qquad \frac{6.2}{2} = 3.1$$

$$\begin{array}{r} 9.853 \\ \underline{-3.10} \\ 6.753 \end{array} \qquad L_m = 6.753 \times .2775 = 1.87 \text{ ft.}$$

CALCULATION OF WETTED SURFACE

The side wetted surface depends on the secondary chine intersection and the wetted height at the transom. The bottom wetted surface depends on the forward keel point and the waterplane intersection with the chine at the after end of the spray area.

These values were observed on the model. From these the wetted surface was computed. Plots of full scale wetted surface

vs chine and keel readings were constructed at the Taylor Model Basin. These plots were used for all models by the use of the scale ratio squared.

REYNOLDS NO. CALCULATION

$$Re = \frac{V\ L_m}{\nu}$$

where

Re = Reynolds No.
V = Speed in Ft/Sec.
L_m = Mean length, ft.
ν = Kinematic viscosity, ft^2/sec.

$$Re = \frac{6.99\ (.187)}{(.92745) \times 10^{-5}} = 1.409 \times 10^6$$

TOTAL RESISTANCE COEFFICIENT CALCULATION

Test points were faired and values of R_t taken at even speed-length ratios from Figures 18 and 19.

$$C_t = \frac{R_t}{\frac{\rho}{2} S_t\ V^2}$$

where

C_t = Total Resistance coefficient

R_t = Total resistance, lbs.

ρ = Density, $\frac{Lb - Sec^2}{FT.}$

S_t = Wetted surface, Ft^2

V^2 = Speed squared, Ft^2/Sec^2

$$C_t = \frac{.720}{\frac{(1.9336)}{2}(1.215)\ (48.86)} = .01255$$

TRIM CALCULATION

$$\frac{\text{Fwd rise} + \text{After rise}}{\text{Base length}} = \sin \tau$$

τ = Change of trim

Shaft angle = 11.9° to the base line.

VERTICAL WEIGHT CALCULATION

Vertical weight = $R \tan \theta$

where

R = Total Horizontal weight, lbs.
$\theta = \tau +$ Shaft angle

This vertical weight was used only on the Webb model and was found to have a considerable influence on trim. The DTMB models were towed by an automatic towing arm which towed along the shaft line at all speeds. The vertical force was not actually measured or recorded.

DATA CALCULATIONS
PRNC-GEN-120

Test Data, Webb Model, Normal Condition, Bare Hull, $\lambda = 27$

$\rho = 1.9336$, $\nu = .92745 \times 10^{-5}$

$V/\sqrt{L}$	R_t	S_t	L_m	$C_t \times 10^3$	$Re \times 10^5$
.5	.0269	1.483	2.25	9.57	3.40
1.0	.141	1.463	2.22	12.71	6.70
1.25	.258	1.44	2.153	15.13	8.13
1.50	.443	1.465	2.21	17.73	10.60
1.75	.555	1.39	2.125	17.20	11.22
2.00	.620	1.308	2.045	15.63	12.34
2.25	.670	1.258	1.962	13.88	13.32
2.50	.721	1.217	1.88	12.48	14.20
2.75	.768	1.161	1.79	11.52	14.86
3.00	.847	1.065	1.692	11.63	15.34
3.25	.904	.905	1.585	12.45	15.57
3.50	.912	.839	1.472	11.68	15.57
3.75	.915	.794	1.407	10.75	15.94
4.00	.916	.765	1.385	9.85	16.74
4.25	.918	.748	1.368	8.95	17.56
4.50	.935	.738	1.355	8.24	18.42

DATA CALCULATIONS

Test Data, Webb Model, Normal Condition with Stimulation, $\lambda = 27$

$\rho = 1.9335$, $\nu = 92633 \times 10^{-5}$

$V\sqrt{L}$	R_t	S_t	L_m	$C_t \times 10^3$	Re $\times 10^5$
.5	.033	1.48	2.25	11.74	3.40
1.00	.152	1.46	2.22	13.71	6.71
1.25	.268	1.44	2.15	15.72	8.14
1.50	.469	1.465	2.21	18.78	10.02
1.75	.600	1.39	2.13	18.59	11.27
2.00	.657	1.33	2.05	16.29	12.39
2.25	.708	1.29	1.97	14.33	13.41
2.50	.768	1.26	1.93	12.87	14.60
2.75	.835	1.21	1.86	12.05	15.49
3.00	.905	1.11	1.75	11.92	15.86
3.25	.941	.965	1.625	12.15	15.98
3.50	.957	.865	1.50	11.89	15.93
3.75	.964	.800	1.43	11.28	16.25
4.00	.977	.761	1.39	10.56	16.82
4.25	.990	.738	1.36	9.78	17.52
4.50	1.07	.730	1.34	9.54	18.26

Test Data for DTMB Model 4020 , λ = 13.5 Normal Displ.

$\rho = 1.9369$, $\nu = 1.0983 \times 10^{-5}$

$V\sqrt{L}$	R_t	S_m	L_m	$C_t \times 10^3$	Re $\times 10^5$
.5	.22	5.74	4.30	9.85	7.83
1.0	1.08	5.72	4.32	12.2	15.73
1.25	1.99	5.70	4.30	14.6	19.42
1.50	3.81	5.70	4.37	19.4	23.71
1.75	4.44	5.59	4.24	16.9	26.87
2.00	4.80	5.36	4.12	14.6	29.82
2.25	5.08	5.14	4.01	12.7	32.68
2.50	5.41	5.00	3.90	11.3	35.33
2.75	5.81	4.66	3.73	10.7	37.18
3.00	6.21	4.38	3.58	10.3	38.91
3.25	6.44	3.91	3.33	10.2	39.17
3.50	6.53	3.58	3.19	9.7	40.43
4.00	6.83	3.58	3.01	8.2	43.60
4.50	7.18	3.16	2.87	7.3	46.77

Test Data for DTMB Model 4021, $\lambda = 11.25$ Normal Displ.

$\rho = 1.9379$, ν 1.1769×10^{-5}

$V\sqrt{L}$	R_t	S_m	L_m	$C_t \times 10^3$	Re $\times 10^5$
.5	.33	8.35	5.20	8.6	9.63
1.0	1.83	8.25	5.16	12.0	19.14
1.25	3.49	8.14	5.12	14.9	23.73
1.50	6.10	7.84	4.98	18.8	2765
1.75	7.40	7.88	5.00	16.6	32.44
2.00	8.10	7.84	4.96	14.0	36.78
2.25	8.55	7.65	4.86	12.0	40.52
2.50	8.98	7.29	4.73	10.7	43.86
2.75	9.67	6.81	4.57	10.2	46.52
3.00	10.30	6.24	4.35	9.9	48.43
3.25	10.61	5.77	4.11	9.5	49.60
3.50	10.83	5.41	3.96	8.9	51.46
4.00	11.39	5.04	3.76	7.7	55.84
4.50	12.00	4.85	3.64	6.6	60.85

Test Data Model 3592-1, λ=9.0 , Normal Displ.

ρ = 1.9379 , ν = 1.1605 $\times 10^{-5}$

$V/\sqrt{L}$	R_t	S_m	L_m	C_t	Re
				X10³	x 10⁶
.5	.62	13.06	6.51	8.3	1.37
1.0	3.72	12.89	6.47	12.5	2.72
1.25	7.43	12.90	6.40	16.0	3.36
1.50	11.90	12.72	6.38	18.1	4.02
1.75	13.95	12.28	6.49	16.1	4.77
2.00	15.12	11.89	6.38	13.8	5.36
2.25	15.98	11.60	6.25	11.8	5.89
2.50	16.88	11.39	6.05	10.3	6.35
2.75	18.20	10.99	5.84	9.5	6.74
3.00	19.52	10.31	5.59	9.1	7.05
3.25	20.41	9.50	5.38	8.8	7.34
3.50	21.00	8.76	5.17	8.5	7.60
4.00	21.92	8.02	4.86	7.4	8.16
4.50	23.09	7.78	4.70	6.4	8.88

Test Data Model 4022, λ = 6.75, Normal Displacement

ρ = 1.9383, ν = 1.2109 $\times 10^{-5}$

$V\sqrt{L}$	R_t	S_m	L_m	C_t $\times 10^3$	Re_λ 10^6
.5	1.85	22.76	8.66	10.7	2.01
1.0	9.10	22.83	8.69	13.0	4.04
1.25	16.40	22.61	8.46	15.1	4.93
1.50	27.20	22.61	8.41	17.4	5.87
1.75	32.60	22.39	8.61	15.5	7.01
2.00	35.25	21.64	8.51	13.3	7.90
2.25	37.40	20.96	8.30	11.5	8.68
2.50	39.75	20.41	8.05	10.2	9.36
2.75	42.35	19.32	7.79	9.4	9.97
3.00	44.95	17.93	7.48	9.1	10.44
3.25	47.20	16.68	7.10	8.7	10.73
3.50	48.60	15.58	6.85	8.3	11.14
4.00	50.85	14.27	6.46	7.3	12.02
4.50	53.85	13.81	6.21	6.3	13.01

Test Data Model 4023, $\lambda = 4.5$, Normal Displacement

$\rho = 1.9379$ $\nu = 1.1769 \times 10^{-5}$

$V\sqrt{L}$	R_t	S_m	L_m	C_t $\times 10^3$	Re $\times 10^6$
.5	5.80	57.85	12.88	9.7	3.76
1.0	28.70	51.45	12.72	12.1	7.45
1.25	54.00	50.61	12.63	14.8	9.26
1.50	88.50	50.12	12.84	17.1	11.28
1.75	109.20	51.36	12.93	15.1	13.26
2.00	118.0	48.64	12.60	13.2	14.75
2.25	125.0	47.90	12.22	11.2	16.12
2.50	132.3	46.42	11.88	9.9	17.39
2.75	141.0	43.70	11.57	9.3	18.63
3.00	150.5	41.23	11.18	8.8	19.66
3.25	157.5	37.53	10.53	8.6	20.09
3.50	162.2	34.32	10.04	8.4	20.60
4.00	168.0	31.85	9.49	7.2	22.22
4.50	—	—	—	—	—

DATA CALCULATIONS

Test Data, Webb Model, Heavy Condition, Bare Hull, $\lambda = 27$

$\rho = 1.9330$, $\nu = .92522 \times 10^{-5}$

$V/\sqrt{L}$	R_t	S_t	L_m	C_t X10^3	Re X10^5
1.75	.649	1.65	2.42	16.95	12.79
2.00	.74	1.575	2.33	15.50	14.07
2.25	.82	1.455	2.20	14.69	14.94
2.50	.882	1.36	2.08	13.68	15.70
2.75	.969	1.29	1.988	13.09	16.51
3.00	1.057	1.262	1.93	12.29	17.50
3.25	1.15	1.258	1.90	11.40	18.66
3.50	1.217	1.24	1.875	10.55	19.83
3.75	1.26	1.175	1.81	10.04	20.51
4.00	1.285	1.02	1.72	10.37	20.79
4.25	1.303	.92	1.65	10.33	21.19
4.50	1.317	.90	1.62	9.52	22.03

DATA CALCULATIONS
PRNC-GEN-126

SUBJECT

Test Data, Webb Model, Heavy Condition, with Stimulation , $\lambda = 27$

$\rho = 1.9335$, $\nu = .92522 \times 10^{-5}$

DATE

SHEET NO. OF SHEETS

LINE NO.	$V\sqrt{L}$	R_t	S_t	L_m	$C_t \times 10^3$	$Re \times 10^5$
1	1.75	.691	1.60	2.47	18.60	13.08
2	2.00	.781	1.51	2.255	17.06	13.65
3	2.25	.838	1.47	2.235	14.86	15.22
4	2.50	.91	1.465	2.23	13.09	16.87
5	2.75	.995	1.45	2.19	11.96	18.22
6	3.00	1.088	1.42	2.12	11.20	19.77
7	3.25	1.194	1.35	2.038	10.26	20.07
8	3.50	1.289	1.22	1.93	11.36	20.46
9	3.75	1.332	1.10	1.82	11.33	20.68
10	4.00	1.35	1.01	1.73	11.00	20.96
11	4.25	1.36	.95	1.675	10.44	21.56
12	4.50	1.38	.92	1.66	9.76	22.62

MODEL RECORDED BY CALCULATED BY CHECKED BY

NAVY-DPPO PRNC, WASH., D.C.

Test Data, Model 4020, Heavy Condition, $\lambda = 13.5$

$\rho = 1.9369$, $\nu = 1.0983 \times 10^{-5}$

$V/\sqrt{L}$	R_t	S_t	L_m	C_t $\times 10^3$	Re $\times 10^5$
.50	.25	6.32	4.72	10.28	8.55
1.00	1.18	6.25	4.70	12.27	17.07
1.25	2.20	6.22	4.63	14.82	20.90
1.50	3.85	6.58	5.02	17.00	27.24
1.75	5.46	6.43	4.84	17.90	30.67
2.00	5.92	6.11	4.70	15.81	34.02
2.25	6.25	5.90	4.62	13.65	37.65
2.50	6.68	5.78	4.54	12.07	41.34
2.75	7.19	5.90	4.44	10.50	44.27
3.00	7.80	5.48	4.31	10.30	46.85
3.25	8.32	5.30	4.13	9.71	48.66
3.50	8.75	4.82	3.95	9.68	50.06
4.00	9.15	4.16	3.68	8.97	53.31
4.50	9.43	3.93	3.48	7.73	56.71

Test Data, Model 4 021, Heavy Condition, λ = 11.25

$\rho = 1.9380$, $\nu = 1.1853 \times 10^{-5}$

$V/\sqrt{L}$	R_t	S_t	L_m	C_t $\times 10^3$	Re $\times 10^6$
.50	.40	9.73	5.8	8.93	1.07
1.00	2.00	8.95	5.67	11.16	2.09
1.25	3.80	8.78	5.48	15.01	2.52
1.50	7.00	9.50	6.05	17.80	3.34
1.75	9.00	9.40	5.85	16.96	3.77
2.00	10.00	9.00	5.72	15.10	4.21
2.25	10.60	8.83	5.60	12.87	4.64
2.50	11.30	8.68	5.50	11.29	5.06
2.75	12.30	8.50	5.40	10.39	5.46
3.00	13.30	8.24	5.25	9.72	5.80
3.25	14.05	7.85	5.08	9.20	6.07
3.50	14.60	7.20	4.88	8.97	6.29
4.00	15.15	6.22	4.50	8.39	6.62
4.25	15.48	6.04	4.37	6.87	7.39

Test Data, Model 3592-1, Heavy Condition, $\lambda = 9.0$

$\rho = 1.9381$, $\nu = 1.1937 \times 10^{-5}$

$V\sqrt{L}$	R_t	S_t	L_m	$C_t \times 10^{3}$	$Re \times 10^{6}$
1.50	12.75	15.1	7.65	16.31	4.68
1.75	16.50	14.83	7.43	15.80	5.30
2.00	19.00	14.20	7.20	14.55	5.88
2.25	20.30	13.86	7.08	12.59	6.50
2.50	21.50	13.50	7.01	11.10	7.15
2.75	23.00	13.22	6.87	10.00	7.71
3.00	24.75	13.03	6.67	9.17	8.17
3.25	26.25	12.40	6.42	8.71	8.51
3.50	27.90	11.60	6.20	8.54	8.86
4.00	29.26	9.80	5.70	8.12	9.30
4.50	30.52	9.25	5.43	7.08	9.98

Test Data, Model 4022 , Heavy Condition, $\lambda = 6.75$

$\rho = 1.9381$, $\nu = 1.1937 \times 10^{-5}$

$V\sqrt{L}$	R_t	S_t	L_m	C_t $\times 10^3$	Re $\times 10^6$
.5	2.00	25.1	9.43	10.47	2.21
1.0	8.90	24.9	9.38	11.67	4.42
1.25	16.00	24.26	9.10	13.73	5.36
1.50	29.00	24.26	9.06	17.31	6.41
1.75	38.30	25.65	9.76	15.90	8.00
2.00	43.20	25.10	9.60	14.04	9.04
2.25	45.8	24.55	9.48	12.00	10.05
2.50	48.5	24.10	9.32	10.50	10.98
2.75	52.0	23.48	9.20	9.53	11.93
3.00	55.7	23.00	9.00	8.76	12.73
3.25	59.7	22.27	8.75	8.27	13.40
3.50	63.2	21.10	8.48	7.97	13.98
4.00	67.5	18.20	7.80	7.56	14.70
4.50	70.9	17.08	7.48	6.68	15.86

Test Data, Model 4023, Heavy Condition, $\lambda = 4.5$

$\rho = 1.9380$, $\nu = 1.1853 \times 10^{-5}$

$V/\sqrt{L}$	R_t	S_t	L_m	$C_t \times 10^3$	$Re \times 10^6$
1.75	128.5	58.8	14.65	15.52	14.89
2.00	144.5	56.8	14.30	13.84	16.60
2.25	153.8	55.3	14.10	11.95	18.29
2.50	162.0	54.0	13.90	10.44	20.18
2.75	172.8	53.2	13.60	9.33	21.74
3.00	186.0	52.0	13.25	8.63	23.10
3.25	199.6	49.3	12.82	8.32	24.21
3.50	209.5	45.3	12.40	8.20	25.22
4.00	222.0	40.5	11.70	7.46	27.17